January 2017

The Impacts Of Lake-Effect Snow On Traffic Volume In Ohio And Indiana, 2011-2015

Daniel Allen Burow

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THE IMPACTS OF LAKE-EFFECT SNOW ON TRAFFIC VOLUME IN OHIO AND INDIANA, 2011-2015

by

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Bachelor of Science, Valparaiso University, 2015

A Thesis

Submitted to the Graduate Faculty
of the
University of North Dakota

in partial fulfillment of the requirements

for the degree of

Master of Science

Grand Forks, North Dakota

May
2017
This thesis, submitted by Daniel Burow in partial fulfillment of the requirements for the Degree of Master of Science from the University of North Dakota, has been read by the Faculty Advisory Committee under whom the work has been done and is hereby approved.

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This thesis is being submitted by the appointed advisory committee as having met all of the requirements of the School of Graduate Studies at the University of North Dakota and is hereby approved.

Dean of the School of Graduate Studies

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Department: Geography

Degree: Master of Science

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Daniel Burow
20 April 2017
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ABSTRACT

Snowfall presents a hazard to drivers by reducing visibility and increasing safe stopping distances. As a result, some drivers cancel trips if snowfall is occurring or forecasted, and traffic volumes often decrease on snowy days. Lake-effect snow is very localized and is thus hypothesized to have a lesser influence on traffic volume than synoptic-scale snow, which usually covers a broader areal extent. Traffic volume in northeast Ohio and northern Indiana is studied using a matched-pair analysis to determine if volumes differ between lake-effect and synoptic-scale snowfall in these regions. While little statistical evidence is found to support this hypothesis, other relationships are discovered: lake-effect traffic volume is shown to be dependent in part on distance from the lake and population density of the surrounding area. Other trends relating traffic volume to time-of-day and accident patterns are also explored. Findings presented herein can assist in transportation planning, risk analysis, and roadway safety.
CHAPTER I
INTRODUCTION

Adverse weather conditions can play a major role in traffic flow, volume, and crash risk. The Federal Highway Administration (FHA) reports that an average of over 210,000 traffic crashes occur during snow or sleet events every year in the United States, and these crashes are responsible for over 700 fatalities per year. Snowy, slushy, or icy pavement also contributes to hundreds of thousands of accidents each year (FHA 2015). Therefore, snowfall, sleet, freezing rain, or snowy and icy pavement conditions can still be hazardous to drivers. A cautious driver is likely to reduce speed, increase following distance, decrease acceleration rate, or even cancel his or her trip altogether during hazardous (particularly snowy and icy) weather conditions (Goodwin 2002; Rutty and Andrey 2014). Other travelers may delay trips or elect to take public transportation. Andrey, et al. (2003) found crash rates to be higher during snowfall than during rainfall in Canada. Changnon (1979) found that many drivers reported unsafe driving conditions, cancelled trips, and increased expenditures on automobile maintenance and repair during the particularly severe winter season of 1977-1978 in Illinois. Riebsame, et al. (1986) noted that efficiency in government-funded winter road maintenance requires accurate snowfall forecasts at a local scale, so that effects of winter storms on transportation can be mitigated. Research on the effects of snowfall on traffic flow and patterns would be useful to transportation officials who regularly monitor traffic flow for infrastructure planning and to prioritize road maintenance and snow removal strategies. Additionally, numerical models have been designed to forecast road
conditions during inclement weather, and accurate quantification of traffic volume during snowfall improves their effectiveness (Crevier and Delage, 2001). Finally, other studies have sought to measure crash risk during inclement weather, which is difficult to accurately calculate unless the number of safe trips are known (Eisenberg and Warner 2005; Abdel-Aty and Pemmanaboina 2006; Mills, et al. 2011; Black and Mote 2015). Since the number of vehicles on the road tends to be smaller during adverse weather conditions, a measure of the rate at which traffic volume decreases during winter weather would be helpful to researchers when comparing bad-weather to fair-weather crash risk.

Hazardous winter weather can also cause traffic pileups. These chain reaction crashes generally occur due to a combination of slick roads, which reduce safe stopping distances further than drivers estimate, and reduced visibility, which impede a driver’s ability to see an accident occurring in front of them. This sort of “domino-effect” can leave dozens or even hundreds of cars damaged, as well as incur multiple injuries or fatalities and render busy highways impassable.

There have been several incidents of large traffic pileups in the southern Great Lakes region. One such pileup occurred on March 12, 2014, in rural Sandusky County, Ohio. The initial collision occurred on the Ohio Turnpike shortly after 1:00 pm and Ohio State Troopers estimated that between 40 and 50 cars were involved. Three people were killed and one seriously injured, and the turnpike was closed in both directions for hours. The Toledo Blade reported that a travel ban was in effect for the area, but authorities rarely enforce such a ban on freeways (Patch 2014).

Another pileup occurred during a lake-effect snow event on the Kennedy Expressway in Chicago on February 15, 2015. The initial crash occurred at 10:15 am. Thirty-eight cars were
involved, and 12 injuries were reported, according to the *Chicago Tribune*. All traffic lanes on the expressway were not reopened until 5:45 pm, seven and a half hours after the initial crash (*Chicago Tribune* 2015). The National Weather Service (NWS) had only called for accumulations of up to two inches of snow for the day, yet hazardous conditions causing the pileup were still realized even with the low snow totals. Black and Mote (2015) suggest that while drivers do adopt some safer driving habits during snowfall, they fail to completely counteract the increased crash risk for poor driving conditions.

A heavier lake-effect snow event reduced visibility to less than a quarter-mile in northern Indiana on January 23, 2014. In the mid-afternoon, a crash on eastbound I-94 swelled to forty vehicles, including eighteen tractor-trailers. Three people were killed, and more than twenty others injured. Lanes were finally opened again the following morning, reported NBC Chicago, and drivers “could only see one or two cars” in front of them, according to one survivor (NBC Chicago 2014).

Lake-effect snow is much more localized and can sometimes be more difficult to model and predict than synoptic-scale snow (Bates, et al. 1993). Drivers may not be able to anticipate poor driving conditions on their trip. Some drivers may plan trips for fair weather and pleasant driving, only to encounter an intense lake-effect snow band. For example, there have been several instances of large traffic pileups within a localized lake-effect band (*Chicago Tribune* 2015; *NBC Chicago* 2014). Several studies have noted an increasing trend in lake-effect snow events as global average temperatures increase (Norton and Bolsenga 1993; Burnett, et al. 2003). This suggests that traffic disruptions due to lake-effect snow will increase in coming years. The purpose of this study is to determine if traffic volume varies in the same way during lake-effect snow as it does during synoptic-scale snow. Fridstrom, et al. (1995) argued that future decreases
in traffic accident rates are not likely to be realized unless overall traffic volume is decreased as well, particularly during poor weather conditions. Thus, a better understanding of patterns in traffic volume may lead to more effective methods of mitigating crash risk. My research hypothesis is lake-effect snow will not decrease traffic volume as drastically as larger, synoptic-scale snow systems when controlled for daily traffic fluctuations, since drivers may not anticipate driving into a localized lake-effect snow band.
CHAPTER II
LITERATURE REVIEW

Traffic Volume and Crash Risk

Eisenberg and Warner (2005) studied the effects of snowfall on crash rates from 1975 to 2000. They found that the first snow day of each year was significantly more hazardous than clear days in terms of crash risk. Subsequent snow days had lower fatality risks, but overall crash risk remained high. This suggests that drivers assume safer driving habits once snow has fallen. The authors also found that older, high-risk drivers avoid driving during most winter snowfalls. However, they reported daily state-level results and extrapolated a few snowfall observations across each state in the United States. Thus, it is difficult to draw conclusions on details of driver habits at a finer spatial and temporal scale. Black and Mote (2015) found a 19 percent increase in crash risk during winter weather events throughout the United States using an arbitrary estimation of safe trips during each event. Fatal crash risk during winter weather days was approximately equal to risk during dry days, but non-fatal injury risk increased by about 13 percent during winter weather. The authors hypothesized that this is because drivers reduce speed and exercise more caution during hazardous conditions. Mills, et al. (2011) also found increased crash risk during winter precipitation events in Winnipeg when analyzing police and insurance records, although their sample size was small and yielded a wide confidence interval when compared to summer precipitation events. Edwards (1999) found that drivers in Wales reduced speeds by about three miles per hour in rainy conditions, although the effects of snowfall were not studied. If a similar pattern holds true for snowfall, perhaps a three mile per hour reduction in driving speed is sufficient to mitigate increases in fatal crash risk, if other factors
such as reaction time are controlled for. Black and Mote (2015) found that variations in crash risk also depend on geographic location. Risks in high snowfall cities like Chicago and Cleveland increased substantially less than in warmer cities like Cincinnati and St. Louis. Andrey, et al. (2003) conducted a similar study for six urban areas in Canada and found that collision risk increased by about 75 percent during precipitation, while injury risks increased by 45 percent during precipitation. These rates tend to be higher during snowfall than during rainfall, although risk increases are not consistent from city to city. Call (2005) suggested similar geographic variations in snowstorm response in upstate New York. Cities closer to Lake Erie, such as Buffalo and Rochester, tended to have effective snow mitigation systems and were more resilient to heavy snowfall totals.

Kilpelainen and Summala (2007) found through their survey of Finnish drivers that older drivers tend to seek additional information about road conditions when faced with trips through adverse weather. These drivers also tended to more frequently make changes to travel plans in response to poor conditions, and leisure trips were found to be less common during snowfall, although quantitative details were not available. In a similar study, Rutty and Andrey (2014) found that nearly all Ontario residents surveyed consulted weather forecasts before planning a winter recreation trip, and concluded that forecasted conditions impact vehicular travel.

Datla and Sharma (2008) concluded that the effect of snowfall and extreme cold on traffic volumes in Alberta, Canada was dependent on many factors such as day of the week, hour of the day, type of roadway, and air temperature. On average, traffic volumes were found to decrease between 7 and 17 percent for every centimeter of falling snow per day, a rate which the authors asserted was consistent with other studies. Weekend traffic and recreational roads tend to be most susceptible to decreased volume, since a higher percentage of trips can be cancelled with
no repercussions. This finding is supported by Cools, et al. (2010), who found that traffic counts in Belgium decreased for a variety of weather-related conditions. Snowfall, in particular, caused a 3.8 percent decrease in traffic counts, on average. One location near the seashore exhibited the strongest correlation to weather conditions, presumably since nearby beaches are a popular leisure destination, and travelers’ visits were more weather-dependent and easily cancellable. Zhang, et al. (2013) determined that traffic volume was most strongly correlated to temperature (lower volumes at lower temperatures) and visibility most strongly correlated to traffic speed (lower speeds during lower visibilities) in Jilin Province, China. A similar study conducted in Scotland by al Hassan and Barker (1999) concluded that weather-related decreases in traffic volume tend to be more extreme on weekends, when a higher percentage of travel was not work related and thus more easily cancellable. Additionally, traffic counts were found to decrease by about 15 percent for days in which snow was on the ground. Maze, et al. (2006) presented traffic volume reductions ranging from 5 to 22 percent while snow was falling, depending on the intensity of snowfall, as well as reductions in average vehicle speed from 3 to 9 miles per hour, again depending on snowfall intensity.

Call (2011) studied the correlation between snow and traffic counts at three toll barriers in upstate New York. He found a statistically significant negative relationship between snowfall and counts at all three locations, and a slightly weaker relationship between temperature and counts. A more detailed look at vehicle type revealed that snowfall produced a sharper reduction in small vehicles than large ones, such as tractor trailers, and the ratio of large vehicles to small ones increased during snowstorms. The author suggests that larger trucks tend to be driven commercially on tighter deadlines, and their drivers are less likely to postpone trips due to adverse weather if conditions are still navigable. Since trucks are more likely to use interstate
highways, it is possible that traffic counts on high-use freeways do not decrease as much in response to snowfall as on more minor roads. This hypothesis was confirmed by Roh, et al. (2015), who found that truck traffic in Alberta was not significantly affected by unseasonable cold or snowfall, suggesting that commercial trucks operate on very strict schedules with little margin for delay due to adverse weather.

The study presented here specifically focuses on traffic volume during lake-effect snow. Although this has not been studied in great detail, Schmidlin (1993) provides a basis for the impacts of lake-effect snow on traffic. Schmidlin (1993) studied the month of December 1989, which was 7.0°C colder than average for northeast Ohio, and yielded excessive lake-effect snow totals downwind of Lake Erie. The author found that traffic counts on Interstate-90 were 3.5 percent lower than the previous December. Additionally, departments of transportation incurred increased snow removal cost, and public transit ridership in Erie, Pennsylvania, was down by about 7 percent (Schmidlin 1993). Call (2011) mentioned that future research could use spatially and temporally dense traffic and snowfall observations, particularly where intense, lake-effect snow is common. This provides a motivation for this research, as we can better seek to understand traffic volume disruption at a finer spatial scale.

**Blowing Snow**

Snow does not need to be actively falling to be hazardous to drivers. Automated decision support systems for transportation officials have been in place since the 1970s, and have taken blowing snow events and associated visibility reductions into account, even if snow was not actively falling (Tabler 1979).

Matsuzawa, et al. (2008) studied driver visibility on the roadway during blowing snow events. The authors found that driver visibility tended to decrease the closer one was to ground
level, due to an increase in snow particle density and snow mass flux nearer to ground level. This effect was exacerbated by the presence of a snowbank on the windward side of the road, as well as a lack of illumination, either man-made or from the sun. This suggests that driving conditions during blowing snow events are worse for low-profile vehicles.

Strong winds are generally able to loft a great amount of snow and cause a greater decrease in visibility, but wind speeds do not need to reach blizzard criteria (35 mph or greater) in order to blow snow and pose a threat to drivers. Li and Pomeroy (1997) determined that the minimum wind speed necessary for snow saltation (lofting) was 7.7 m/s (17 mph) on average. However, saltation was observed with wind speeds as low as 4 m/s (9 mph), provided snow was not exposed to above freezing temperatures. These thresholds are commonly reached, even during relatively fair conditions, so it can be concluded that snow does not even need to be actively falling to prove a driving hazard.

Lake-Effect Snow

Most of the aforementioned studies on traffic volume and accidents use a fairly coarse spatiotemporal scale (Eisenberg and Warner 2005), or examine areas away from large water bodies where snow more often occurs due to synoptic-scale snowstorms (Andrey, et al. 2003; Datla and Sharma 2008; Zhang, et al. 2013). These larger-scale storms tend to cover larger spatial areas and are often easier to forecast and publicize. Lake-effect snow, on the other hand, is very localized. The exact location of snowfall during these events is dependent on fine-scale low level wind patterns, which are difficult to measure and predict (Bates, et al. 1993). These events tend to occur during dominant high pressure regimes, so locations outside of the immediate snowfall band often experience clear skies and fair driving conditions (Ellis and Leathers 1996; Notaro, et al. 2013). “[Conditions] went from sunshine to complete no visibility,
so when [cars] entered in, it turned into slide off, crash, crash, and multiplied…,” one survivor of the January 2014 pileup on I-94 in Indiana told reporters (NBC Chicago 2014). Travelers may not be aware of the possibility of locally hazardous conditions when driving or planning their trip. Figure 1 is a reflectivity map of lake-effect snowfall in northwest Indiana. Note how snowfall intensity varies from clear air through most of northern Indiana to heavy snowfall between Michigan City and Gary over a span of forty kilometers (25 miles).

Figure 1. Radar reflectivity map of an intense lake-effect snow band in northwest Indiana on January 2nd, 2014. 850 millibar heights are overlaid in decameters. Sources: National Centers for Environmental Information (NCEI), North American Regional Reanalysis (NARR), NOAA.

Lake-effect snowfall occurs when cold, dry air moves over a large lake. Moisture from the relatively warm lake condenses in the cold airmass aloft to form clouds, occasionally forming precipitation (Niziol 1987). Lake-effect snow is most common in late fall and early winter when
unfrozen lake waters are warmest relative to overlying air and local instability is maximized (Notaro, et al. 2013). Later in winter, lake temperatures cool down and sufficient instability is less common (Niziol, et al. 1995). Eichenlaub (1979) studied mean annual snowfall in the Great Lakes states and found higher precipitation totals downwind of each lake. Particularly high annual snowfall rates were found in the Upper Peninsula of Michigan, Upstate New York, and extreme northwest Pennsylvania. Parts of northwest Indiana and northeast Ohio also receive two to three times as much annual snowfall as other locations at similar latitudes that are further from the Great Lakes (Changnon, et al. 2006; Houston and Changnon 2009).

There are no strict thresholds that define lake-effect snow through observations, but lake-effect snow does tend to exhibit higher snow-to-liquid ratios than synoptic-scale snow for a given temperature profile (Schmidlin, et al. 1992). Baxter, et al. (2005) found that areas immediately downstream of the Great Lakes experience a long-term mean snow-to-liquid value of 13:1 or greater as they are heightened more so than nearby locations immediately east or west of the lake. Strong instability in the boundary layer and low cloud levels in lake-effect convection allow for higher ratios, particularly as the band reaches further inland and snowflake riming decreases (Jiusto and Weickmann 1973).

Hjelmfelt (1990) defined four separate morphologies of lake-effect snow on Lake Michigan. One common pattern is a narrow, but intense band of convection and snowfall, generally occurring when prevailing winds are parallel to the long fetch of the lake (north to south). These types of events can dump intense snow totals on parts of northwest Indiana and southwest Michigan, at the southern end of Lake Michigan, while nearby locales remained clear and dry. On Lake Erie, similar patterns can cause prolonged snow events in far western New York and northwest Pennsylvania when steering winds are out of the west-southwest (Niziol
Another pattern identified by Hjelmfelt (1990) occurs when dominant winds blow perpendicular to the long fetch of the lake. Snowfall occurs over a greater area, but tends to be less intense. This commonly causes snowfall on the eastern shores of Lake Michigan and the southern shores of Lake Erie, Ontario, and Superior. Lake-effect precipitation from Lake Michigan and Lake Superior occurs most frequently between 0200 and 0900 CST, when horizontal thermal gradients between lake and land temperatures are greatest (Kristovich and Spinar 2005).
CHAPTER III
METHODOLOGY

Study Area

The southern Great Lakes region of Indiana and Ohio is an ideal area for study. Mean annual snowfall in the northern part of each state ranges from 75 centimeters (30 inches) in northwest Ohio and northeast Indiana to over 250 centimeters (100 inches) in northeast Ohio due to the influence of nearby Lake Erie. Each state has large urban areas, such as Indianapolis, Cleveland, and Columbus, and includes expansive rural areas and open countryside that may be subject to whiteout conditions during inclement weather. Lake-effect snow is common in northeast Ohio and northwest Indiana, due to their proximities to Lake Erie and Lake Michigan.

Ohio and Indiana are also the location of important overland transportation corridors through the country. Nearby Chicago is a major transportation hub, and is connected to other large cities such as St. Louis, Indianapolis, and Milwaukee via the interstate highway network. Indiana prides itself on being the “Crossroads of America”, and many major east/west routes, such as I-80/90 and I-70, run through both states (Indiana Historical Bureau).

The Ohio and Indiana Departments of Transportation contract out to the firm MS2 for traffic data management. MS2 is a company that designs and hosts software for transportation analytics, and is based in Ann Arbor, Michigan. Since both DOTs use the services of MS2, traffic data collection is presumably consistent across all three states.
The study period ranges from January 2012 until the March 2015. January of 2012 is the first month with a full range of MS2 traffic data for the study. There is a total of 294 traffic counters that continuously monitor traffic volume among the three states including 98 in Indiana and 196 in Ohio. These counters keep track of vehicles traveling past their location by the hour. Some are no longer active, but their counts are still archived by MS2 and their respective DOT. Counters are placed on busy interstates as well as minor arterial roads. Figure 2 shows the locations of continuous traffic counters within the study region that have counts for at least 100 separate days since 2011. There are many more traffic counters across the region, although most take counts for only a few days per year; these infrequent traffic counters were omitted from this study.
Weather conditions are observed and archived by the National Oceanic and Atmospheric Administration (NOAA). Observations are taken every hour by instrument sensors located at most airports. These usually include air temperature, wind speed, visibility, precipitation type
and accumulation, as well as other measures. Precipitation, wind speed, wind direction, and temperatures are the only variables used in this study. NOAA weather and radar archives can be used to interpolate driving conditions at any of the continuous traffic counters.

Event Identification of Lake-Effect Snow

A set of snow events for each study region (Indiana and Ohio) was identified and selected for study on a daily scale using several meteorological factors common to lake-effect or synoptic-scale snow. National Weather Service daily weather observations from Cleveland, Ohio (KCLE) and South Bend, Indiana (KSBN) were obtained for the months of December to March for December 2011 to March 2015. Climatologically, these months are the snowiest of the year in the Great Lakes region. December and January are particularly conducive to lake-effect events due to very cold air masses moving over relatively warm lakes, producing the requisite instability for cloud formation and snowfall. Days with snowfall at the aforementioned observation stations were identified from these records and further classified as a possible lake-effect event by using a set of meteorological criteria.

The first criterion was sub-freezing temperatures throughout the day in question. Naturally, this is necessary for precipitation to fall as snow. In addition, and to complicate road hazards, temperatures above freezing can lead to melting and freezing patterns throughout the day, freezing rain, mixed wintry precipitation, ice accumulation, or other precipitation types that may affect driving conditions to a greater extent than pure snowfall. Since these other mixed precipitation types can be localized (and not often captured by NWS observations) and are beyond the scope of this research, days with possible mixed precipitation types were excluded. High temperatures on the day in question were also expected to be lower than previous days.
Such a pattern is indicative of cold air advection moving into the study region, and this cold air advection is critical in producing instability for cloud formation over and downwind of the lake in a lake-effect setup. This component was not critical to identification, but did add confidence if present.

The second criterion for a lake-effect classification was the presence surface winds on the day in question from the direction of the lake. This is also dependent on the orientation and long axis of the lake in question – northerly flow over Lake Michigan will move over a longer fetch and produce a narrower band than a similar pattern over Lake Erie. However, westerly flow over Lake Erie will produce a wider area of snowfall over northeast Ohio than over northern Indiana. Minimal directional wind shear in the lower and mid-levels of the atmosphere is ideal to maintain lake-effect snowstorms, and this (as well as low level cold air advection) can be verified using atmospheric reanalyses such as the North American Regional Reanalysis (NARR) maintained by the National Oceanic and Atmospheric Administration (NOAA). Too much directional turning in the low-level wind field can act to tear apart lake-effect setups, and greater directional shear is more common in synoptic-scale snow events.

The third criterion for a lake-effect snow event is a high snow-to-liquid ratio. This can be due to several factors – arctic air masses that induce lake-effect snowfall make for lighter, fluffier snow with higher snow-to-liquid ratios. The warmth and instability of the lake surface can lead to strong instability and rising motion in snowstorms with dendritic growth zones (the layer in the atmosphere in which temperatures are between -10°C and -20°C, where snowflake formation is most efficient) closer to ground level than is commonly found in synoptic-scale systems. These factors combine for more efficient snow formation and minimal snowflake sublimation before reaching the surface, which produces high ratios that are evident in long-term
snow-to-liquid climatologies (Baxter, et al. 2005). These ratios can easily be derived from observations by dividing daily snowfall into daily liquid accumulation.

If a given day’s observations at Cleveland or South Bend met the aforementioned criteria (sub-freezing temperatures, winds from the lake, and high snow-to-liquid ratios), radar archives were consulted for imagery from the Cleveland (KCLE), Northern Indiana (KIWX), and Chicago (KLOT) radars. National radar composites are archived by the Iowa Environmental Mesonet and offered through NOAA’s National Centers for Environmental Information (NCEI). Typical lake-effect reflectivity patterns exhibit localized, but spatially continuous reflectivities originating from the direction of the lake and moving onshore. An example of this can be seen in Figure 1. A key factor is that areas outside the lee of the lake did not receive snowfall during suspected lake-effect events – such a pattern would indicate that snowfall was originating from locations other than the Great Lakes. Most days with lake-effect snow setups will see snowfall coming off of multiple nearby lakes. Thus, a suspected lake-effect day will probably exhibit similar precipitation patterns downwind of several of the Great Lakes. In the context of traffic flow, drivers coming from areas not in the lee of the lake may not anticipate lake-effect snowfall along their journey, so the location and areal extent of the snowfall with respect to the lake and wind direction was critical to classify an event as lake-effect in nature.

Similar patterns in remotely-sensed cloud patterns added confidence to an event’s classification. Cold air advection necessary for lake instability is usually accompanied by high pressure moving into the region, producing clear skies in areas outside the lee of the lake (Ellis and Leathers 1996). Therefore, lake-effect cloud patterns in satellite imagery will resemble those of radar reflectivities – localized to the lee of the lake and clear upwind and further inland. Satellite imagery has long been used to identify lake-effect snow locations and can compensate
for gaps in radar coverage (Ferguson 1971; Holroyd 1971; Kristovich and Steve 1995). The Cooperative Institute for Meteorological Satellite Studies (CIMSS) archives daily imagery from the Moderate-Resolution Imaging Spectroradiometer (MODIS) at one kilometer resolution that was used to further verify the origin of snow-producing clouds. Figure 3 shows examples of the difference in satellite imagery between a lake-effect event and a synoptic event: the image on the left shows lake-effect clouds developing on Lake Michigan and moving into Michigan and northern Indiana, while the image on the right shows a synoptic-scale system with some lake-effect clouds over Lake Superior.

If a given day met both meteorological and remotely-sensed criteria, it was classified as a lake-effect snow event for the duration of snowfall in the study area on that given day. It is not uncommon for synoptic-scale snowfall (which does not meet the above criteria) to be enhanced in both intensity and areal coverage by lake instability near the shoreline. However, these specific events (a “lake-enhanced” synoptic event) were not classified as lake-effect for the
purposes of this study within the broader context of the research question: drivers would be better aware of poor driving conditions for a synoptic event with broader areal coverage, even with some lake enhancement. Therefore, these lake-enhanced synoptic events were excluded from lake-effect classification.

Event Identification of Synoptic-Scale Snow

Synoptic-scale snow events were classified using a similar system, albeit with less rigid meteorological criteria. Sub-freezing high temperatures were still required in synoptic events to avoid including days with mixed precipitation. Wind direction and temperature relative to previous days can vary somewhat with synoptic-scale snowfall, although some patterns are common. Strongest snowfall tends to occur on the northwest side of a surface low, where low level winds are usually from the northeast. Temperatures also tend to decrease while and after a cyclone moves through, particularly because warm air advection is common with southerly flow beforehand, although strong temperature advection is not as critical for the formation of synoptic snowfall. The most important factor for identifying synoptic-scale snow in this study was the spatial pattern of radar and satellite imagery during each event, since clouds and radar reflectivities are of a broader areal extent and not confined to the lee of the lake.

Classification Results

The above classification strategies were utilized for northern Indiana and northeast Ohio individually to produce two separate sets of lake-effect and synoptic snow events in both study areas. If a given event was not easily and confidently classified one way or another, it was
excluded from study. This approach yielded 34 lake-effect events in northern Indiana and 23 such events in northeast Ohio during the 2011 to 2015 study period. Of these 34 events in Indiana, 15 events were randomly selected for study, as well as 15 of 23 lake-effect events in Ohio. Similar to Call (2011), events over the holiday season in late December and early January were not studied since traffic patterns and travel plans vary substantially from the typical workweek, leading to issues in controlling for such pattern changes.

The synoptic-scale classification procedure identified 22 synoptic-scale snow events over the study period in northern Indiana, and 20 in northeast Ohio. These totals do not include days with mixed precipitation or lake-enhanced synoptic snow to maintain the integrity of the classification. Similar to the procedure with lake-effect events, 10 of the 22 synoptic events in Indiana and 10 of the 20 events in northeast Ohio were selected for study.

Since synoptic-scale snow events are characterized by broader areal coverage, snowfall will be occurring at a greater number of traffic counters for each individual event, meaning that more observations can be taken from a given hour of synoptic-scale snowfall versus lake-effect snowfall. Thus, there is less need for many synoptic events to obtain enough observations for study, and fewer were selected.

Radar

For each selected event (15 lake-effect events in each state and 10 synoptic events in each state), radar data was obtained from NCEI’s NEXRAD data inventory for the duration of the event, up to 24 hours. One hour accumulated precipitation was used to estimate the locations at which snow was falling. Accumulated precipitation is essentially an aggregation of reflectivities detected by the radar during each volume scan for the desired duration (one hour in this case).
The radar can then use several different algorithms to calculate the intensity of precipitation and estimate the amount that has fallen. The algorithm used in this instance is the Precipitation Processing System (PPS), and it is most commonly used for estimating flash flood potential in instances of extreme rainfall. Flood risk is well outside the scope of this work, but the accumulated precipitation product allows for the precise location of snowfall to be mapped with the best possible accuracy.

While precipitation intensity is calculated by the PPS algorithm, this and other algorithms use a reflectivity/rain rate (commonly referred to as a “Z/R relationship”) that is better attuned to raindrops than snowflakes (Matrosov 1992). Reflectivity/snow rates (Z/S relationships) have been established, although accuracy and error varies substantially from event to event (Otahe and Henmi 1970; Boucher and Wieler 1985). Braham, et al. (1992) were able to increase Z/S accuracy in lake-effect snowfall using airborne in-situ observations, but since that was not possible for this study, I did not account for the intensity of the snowfall at any given location, as this measure is not sampled reliably enough for any in-depth statistical procedure. Base reflectivity would perhaps give a better sense of precipitation intensity; but, since lake-effect snow conditions can change rapidly over relatively short periods of time (Niziol 1987), base reflectivity data at any given time may not be well representative of conditions as recently as an hour (the temporal scale of the traffic data) previously.

Other disadvantages to using radar to determine snowfall location relate to the height of the beam above ground level. The lowest beam tilt used by weather radars is 0.5° above ground level. However, this angle assumes that the ground surface is flat. Due to the curvature of the Earth, this is not technically true. A beam that is very close to ground level at short distances from the radar will increase in height above ground level due to its own tilt and the curvature of
Earth’s surface as the beam moves further from the radar. Therefore, at longer distances from the radar, the beam will be at greater height and less representative of precipitation (or a lack thereof) at ground level. Either one of two errors can occur here: 1) a high radar beam can miss snowfall confined to the lowest few kilometers of the atmosphere (as lake-effect snow commonly is); or, 2) it can detect snowfall aloft that completely sublimates by the time it reaches ground level, resulting in radar returns despite clear surface conditions. Niziol (1987) suggested that radar data should not be relied upon to detect lake-effect snowfall, a relatively shallow atmospheric phenomenon, at distances greater than 90 kilometers from the radar. Although Niziol (1987) used an earlier generation of radars (WSR-57) at the time of that work, the same principle applies to radars used by the National Weather Service today (WSR-88D). The NWS radar in Cleveland (KCLE) is able to sample a vast majority of the study area in Ohio within a 90-kilometer radius, but the NWS radar in North Webster, Indiana is not able to reach the westernmost counties in the Indiana study area within a 90-kilometer distance. Therefore, radar data from the NWS Chicago radar (KLOT) in Romeoville, Illinois, was used to supplement snowfall events occurring in far northwest Indiana, including Lake, Porter, Jasper, and Newton Counties.

The inverse of this is also true: low beams very near to the radar can detect non-meteorological objects that the radar still senses as precipitation. This is commonly referred to as anomalous propagation, or “ground clutter”. This situation is more common during superrefraction, when the beam bends more towards Earth’s surface than expected, which is common during particularly cold and stable atmospheric conditions. Since lake-effect snow is also common during cold air surges, reflectance very near to the radar during lake-effect events may not be actual precipitation. In order to take this into account, traffic counters located within...
eight kilometers of the radar were excluded from the study since radar reflectances detected there may not be meteorological in nature. Of the traffic counters in Ohio, 16 were excluded for this reason; however, none of the Indiana counters were located within this distance of the KIWX radar. Beam height at an eight-kilometer (five-mile) distance from the radar can be approximated using the following equation:

\[
 Beam \ Height = R \sin(\phi) + \frac{R^2}{2IR * R_e} 
\]

in which R represents the range from the radar (eight kilometers), \( \phi \) represents the beam elevation angle (0.5°), IR is an approximation of the refractive index of Earth’s atmosphere near the surface (1.21), and \( R_e \) is the radius of Earth (6371 kilometers). Inserting these values into the above equation yields an approximate beam height of 78.11 meters (256.3 feet). Although this assumes normal atmospheric conditions, ground-based objects further than eight kilometers from the radar and substantially less than this height are not likely to produce radar returns that may be confused for falling snow and thus compromise the integrity of the data. Table 1 shows beam heights, assuming normal atmospheric conditions, at six distances from the radar. Lake-effect snowfall would have to be occurring at these heights for the radar to detect them at each respective distance.

<table>
<thead>
<tr>
<th>Distance from Radar (kilometers)</th>
<th>Beam Height (meters)</th>
<th>Beam Height (feet)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8 (minimum)</td>
<td>78.11</td>
<td>256.28</td>
</tr>
<tr>
<td>10</td>
<td>100.24</td>
<td>328.86</td>
</tr>
<tr>
<td>30</td>
<td>378.54</td>
<td>1241.94</td>
</tr>
<tr>
<td>50</td>
<td>760.63</td>
<td>2495.49</td>
</tr>
<tr>
<td>70</td>
<td>1246.48</td>
<td>4089.51</td>
</tr>
<tr>
<td>90 (maximum)</td>
<td>1836.12</td>
<td>6024.01</td>
</tr>
</tbody>
</table>
Although this radar-based method is not without its shortcomings, which have been addressed as mentioned above, it does allow for the location of falling snow to be determined in the most spatially accurate manner. While NOAA does maintain a high-quality network of Automated Surface Observing System (ASOS) stations throughout the study area, they are at a spatial scale that is sufficient to approximate air temperature and wind conditions in surrounding locations but not fine enough to determine fine-scale precipitation locations for the purposes of this research. Spatial density is vital in this instance because lake-effect snowfall can be such a localized phenomenon. A given snow band may set up between ASOS stations, which may not report measurable snowfall, yet substantially affect traffic on roadways between them. Thus, accumulated precipitation products from NWS NEXRAD radars were determined to be the most effective method of delineating the timing and placement of snowfall events with precision.

Traffic Count Procedure

One-hour accumulated precipitation data was obtained and overlaid onto a map of MS2 traffic counters in ArcGIS 10.4 (ESRI, Redlands, CA) for each hour of each event (lake-effect and synoptic) selected by the above methodology in order to determine which traffic counters received snowfall during the hour in question. The hourly traffic volume at each “snowy” counter was obtained from the MS2 database and compared to volume from a dry control period in order to account for daily traffic fluctuations due to rush hour, etc. Dry control periods were selected as the same hour of the same day of the week, exactly one, two, or three weeks before or after the given snowfall event. These control periods were meant to represent “normal” traffic conditions, so the weather on the control day had to be free of precipitation and unseasonably warm or cold temperatures, as temperature has been shown to have a correlation with traffic
volume (al Hassan and Barker 1999; Cools, et al. 2010). Days over the holiday season (late December to early January) were not selected as control periods since traffic patterns would likely differ at those times.

Traffic rates for each counter during every hour of each snowfall event were calculated by dividing the snow volume by the control volume. Thus, if a given counter reported a volume of 90 vehicles during a given snowy hour, and the same counter reported 100 vehicles during the selected dry control period, the rate at that counter would be 0.9 for that hour (90 vehicles / 100 vehicles). A rate over 1.0 indicates that volume was higher during the snow event than during the control event. While not common, some rates over 1.0 were observed in the study, as discussed in following sections. Lower rates were indicative of fewer vehicles on the road during snow events, showing that snowfall played a larger role in traffic volume disruption.

Due to the varying location of the selected lake-effect snow events, as well as varying degrees of completeness in MS2 traffic records, some traffic counters were better sampled through the above methodology than others. Counters with at least 30 observations (hourly matched-pairs) of traffic volume during lake-effect events were selected for further study to determine if traffic volume was significantly higher during lake-effect events than it was during synoptic-scale snow events. This threshold left 33 counters – 29 in Ohio and four in Indiana. Of these 33 counters, three were insufficiently sampled by selected synoptic snow events (fewer than 30 observations), and three were excluded because they were located within three miles of another better-sampled counter, leading to issues regarding spatial autocorrelation of traffic count data. Thus, 27 counters were adequately spaced and sampled for detailed study. Figure 4 is a map of these counters.
Figure 4 shows the location of the 27 sufficiently sampled counters that did not violate the aforementioned spacing threshold and were thus used for the following statistical procedures. Most (23) are in northeast Ohio, not far from Lake Erie. The remaining four are in northern Indiana, and they are generally further from Lake Michigan than the Ohio counters are from
Lake Erie. The relative lack of counters in northern Indiana can be attributed to the scarcity of counters in that region of the state (see Figure 2).
CHAPTER IV

RESULTS AND DISCUSSION

Difference Testing of Lake-Effect and Synoptic Rates

Table 2 shows the average traffic rates during lake-effect and synoptic-scale snow events for these 27 counters. Fifteen counters had higher mean lake-effect rates than synoptic rates, indicating synoptic-scale snow caused a bigger decrease in traffic volume, on average, at these locations. The other twelve counters had higher synoptic rates.

<table>
<thead>
<tr>
<th>Counter Identification</th>
<th>Number of Lake-Effect Observations</th>
<th>Average Lake-Effect Rate</th>
<th>Number of Synoptic Observations</th>
<th>Average Synoptic Rate</th>
<th>Synoptic Rate – Lake Effect Rate</th>
<th>Distance from Lake (kilometers)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6604</td>
<td>41</td>
<td>0.936</td>
<td>61</td>
<td>0.942</td>
<td>0.006</td>
<td>13.192</td>
</tr>
<tr>
<td>19885</td>
<td>53</td>
<td>0.886</td>
<td>78</td>
<td>0.846</td>
<td>-0.040</td>
<td>54.271</td>
</tr>
<tr>
<td>24843</td>
<td>99</td>
<td>0.870</td>
<td>74</td>
<td>0.907</td>
<td>0.037</td>
<td>2.117</td>
</tr>
<tr>
<td>25243</td>
<td>34</td>
<td>0.935</td>
<td>67</td>
<td>0.972</td>
<td>0.037</td>
<td>4.001</td>
</tr>
<tr>
<td>30967</td>
<td>72</td>
<td>1.082</td>
<td>75</td>
<td>0.975</td>
<td>-0.107</td>
<td>30.765</td>
</tr>
<tr>
<td>57377</td>
<td>62</td>
<td>0.890</td>
<td>82</td>
<td>0.870</td>
<td>-0.020</td>
<td>31.620</td>
</tr>
<tr>
<td>71877</td>
<td>42</td>
<td>0.868</td>
<td>72</td>
<td>0.870</td>
<td>0.002</td>
<td>40.900</td>
</tr>
<tr>
<td>76877</td>
<td>75</td>
<td>0.874</td>
<td>82</td>
<td>0.876</td>
<td>0.002</td>
<td>24.115</td>
</tr>
<tr>
<td>75777</td>
<td>32</td>
<td>0.871</td>
<td>81</td>
<td>0.866</td>
<td>-0.005</td>
<td>48.495</td>
</tr>
<tr>
<td>75877</td>
<td>37</td>
<td>0.865</td>
<td>84</td>
<td>0.890</td>
<td>0.025</td>
<td>50.757</td>
</tr>
<tr>
<td>76677</td>
<td>57</td>
<td>1.014</td>
<td>79</td>
<td>0.918</td>
<td>-0.096</td>
<td>35.826</td>
</tr>
<tr>
<td>76777</td>
<td>42</td>
<td>0.916</td>
<td>76</td>
<td>0.982</td>
<td>0.066</td>
<td>45.396</td>
</tr>
<tr>
<td>92218</td>
<td>35</td>
<td>0.879</td>
<td>70</td>
<td>0.892</td>
<td>0.013</td>
<td>0.678</td>
</tr>
<tr>
<td>92318</td>
<td>92</td>
<td>0.861</td>
<td>82</td>
<td>0.894</td>
<td>0.033</td>
<td>17.150</td>
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<tr>
<td>92518</td>
<td>102</td>
<td>0.834</td>
<td>34</td>
<td>0.824</td>
<td>-0.010</td>
<td>7.648</td>
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<tr>
<td>92818</td>
<td>129</td>
<td>0.846</td>
<td>100</td>
<td>0.907</td>
<td>0.061</td>
<td>9.979</td>
</tr>
<tr>
<td>93218</td>
<td>92</td>
<td>0.833</td>
<td>86</td>
<td>0.895</td>
<td>0.062</td>
<td>5.005</td>
</tr>
<tr>
<td>93418</td>
<td>109</td>
<td>0.930</td>
<td>84</td>
<td>0.923</td>
<td>-0.007</td>
<td>0.242</td>
</tr>
<tr>
<td>94118</td>
<td>93</td>
<td>0.926</td>
<td>81</td>
<td>0.888</td>
<td>-0.038</td>
<td>23.123</td>
</tr>
<tr>
<td>97647</td>
<td>40</td>
<td>0.854</td>
<td>72</td>
<td>0.879</td>
<td>0.025</td>
<td>4.381</td>
</tr>
<tr>
<td>99752</td>
<td>57</td>
<td>0.911</td>
<td>72</td>
<td>0.868</td>
<td>-0.043</td>
<td>31.825</td>
</tr>
<tr>
<td>115618</td>
<td>78</td>
<td>0.862</td>
<td>72</td>
<td>0.880</td>
<td>0.018</td>
<td>12.777</td>
</tr>
<tr>
<td>121418</td>
<td>32</td>
<td>0.913</td>
<td>70</td>
<td>0.910</td>
<td>-0.003</td>
<td>15.815</td>
</tr>
<tr>
<td>990201</td>
<td>57</td>
<td>1.013</td>
<td>58</td>
<td>0.872</td>
<td>-0.141</td>
<td>76.926</td>
</tr>
</tbody>
</table>
Table 2 continued.

<table>
<thead>
<tr>
<th>Counter Identification</th>
<th>Number of Lake-Effect Observations</th>
<th>Average Lake-Effect Rate</th>
<th>Number of Synoptic Observations</th>
<th>Average Synoptic Rate</th>
<th>Synoptic Rate – Lake Effect Rate</th>
<th>Distance from Lake (kilometers)</th>
</tr>
</thead>
<tbody>
<tr>
<td>990202</td>
<td>58</td>
<td>0.989</td>
<td>53</td>
<td>0.889</td>
<td>-0.010</td>
<td>80.453</td>
</tr>
<tr>
<td>990203</td>
<td>60</td>
<td>0.989</td>
<td>71</td>
<td>0.819</td>
<td>-0.170</td>
<td>93.499</td>
</tr>
<tr>
<td>954500</td>
<td>31</td>
<td>1.046</td>
<td>57</td>
<td>0.877</td>
<td>-0.169</td>
<td>18.682</td>
</tr>
</tbody>
</table>

The non-parametric Wilcoxon matched-pair signed-rank test was applied to these 27 counters. Ideally, a simple difference-of-means or other parametric test would be used in this instance. Given the relatively small number of well-sampled counters, the Wilcoxon test was used to determine if synoptic-scale snow caused significantly sharper decreases in traffic volume than lake-effect snow. Figure 5 is a histogram showing the relationship between mean synoptic rate and mean lake-effect rate for these 27 counters. Figure 5 is skewed left, indicating that lake-effect rates were substantially higher than synoptic rates for several counters.

![Figure 5](image.png)

**Figure 5.** Histogram of differences in mean rates between synoptic and lake-effect rates. Source: MS2.

The Wilcoxon signed rank test for these counters yielded a test statistic of -1.057 and a p-value of 0.146, which is not statistically significant at the $\alpha = 0.05$ level. This finding suggests that, while there is a trend towards lower traffic rates during synoptic events as compared to
lake-effect events, the difference is not significant for the counters included in this study. As can be seen in Figure 5, there is some variance between counters that warrants further investigation, and some of this variance can be attributed to the differences in counter location.
Traffic Counters in Study Region

Figure 6. Rate difference (synoptic rate – lake-effect rate) in northeast Ohio. Source: MS2, ESRI, U.S. Census Bureau.
Figure 6 is a map of the differences in mean rates (synoptic rate minus lake-effect rate) for 25 traffic counters, focused on Cleveland and Akron, Ohio for detail. Although the statistical tests mentioned in this work included four counters in Indiana, Figure 6 highlights the counters in Ohio. These differences (mean synoptic rate minus mean lake-effect rate) tend to be more positive along the Lake Erie shoreline, which indicates that lake-effect snowfall causes more of a disruption in traffic volume than synoptic snowfall in these areas. However, further inland, the differences are more negative and the opposite is true; synoptic snow causes more of a disruption in traffic volume. This pattern is the case for the Indiana counters, which are located further from the lake than the Ohio counters (see Figure 4). For Ohio and Indiana, this is possibly because lake-effect snow bands coming from Lake Erie (and Lake Michigan) will dissipate as they move further inland, and this weakening in intensity will cause less disruption in traffic volume at points located further from the lake. This trend is further investigated in Figure 7.

![Rate Difference vs. Distance from Lake](image)

> Figure 7. Relationship between distance from the lake (Erie or Michigan) and difference between lake-effect and synoptic rates. Differences substantially far from the trendline are circled in Figure 7 and mapped in Figure 8. Source: MS2.
Figure 7 shows the relationship between mean synoptic and lake-effect rates (y-axis) and distance from Lake Erie (for Ohio counters) or Lake Michigan (for Indiana counters). The correlation yields a Spearman’s rank correlation of -0.53 and a p-value of 0.005, which is statistically significant at the $\alpha = 0.05$ level. Therefore, counters further from the lake experience less of a disruption in traffic volume due to lake-effect snow than synoptic-scale snow, likely because of a decrease in lake-effect snowfall intensity at inland locations. The points between 40 and 55 kilometers from the lake (circled in red) are substantially above the trendline, indicating that lake-effect snow rates are lower than expected at these counters. The inverse is true for points circled in blue, on the opposite side of the trendline, where lake-effect rates are higher than expected. The locations of these points in northeast Ohio are highlighted in Figure 8.
Figure 8. Locations of low and high LE rate differences (see Figure 7) with respect to distance from Lake Erie. Although data from Indiana counters is included in Figure 7, Figure 8 focuses on northeast Ohio for the sake of detail. Sources: MS2, U.S. Census Bureau, ESRI, CIESIN.

Figure 8 is a map of traffic counters overlaid on a map of population density, from the Center for International Earth Science Information Network. The map shows that counters with a
more positive difference in average lake-effect and synoptic rates than expected given their
distance from Lake Erie (shaded red in Table 2, circled in red in Figure 7, plotted in red in Figure
8) are in urban areas of greater Akron. Inversely, higher rates (blue in Table 2, Figure 7, and
Figure 8) are in the more rural region between the Cleveland and Akron metro areas. This pattern
suggests that traffic rates during lake-effect snow events are higher in rural areas than urban
areas, a relationship that is shown in Figure 9.

Figure 9 shows that well-sampled counters in more urban areas, where population density
is higher, are characterized by lower rates during lake-effect snowfall. The Spearman’s rank
correlation for this relationship is equal to -0.581 with a p-value of 0.0015, which is also
statistically significant at the $\alpha = 0.05$ level. As shown in Figures 7 and 8, counters located further inland in Akron (red) had lower rates during lake-effect snowfall than counters closer to the lake (blue) in rural areas. This suggests that population density of the surrounding area plays a role in traffic volume during lake-effect snow events. This may be because drivers in urban areas tend to take more cancellable trips or have the option to take public transportation if weather conditions are poor. Long-distance drivers in more rural areas do not have the latter option, which accounts for higher lake-effect snow rates.

![Synoptic Rate vs. Population Density](image)

Figure 10. Relationship between mean traffic rate during synoptic-scale snowfall and population density. Source: MS2.

However, this trend between lake-effect snow rate and population density may be partially attributable to the location of densely populated areas of northeast Ohio. These areas near the Lake Erie shoreline likely see more intense lake-effect snow events, which tend to lower traffic volumes. Figure 10 lends credence to this possibility, showing that the relationship
between traffic rates and population density is unique to lake-effect snow – a trend not found in these same counters during synoptic-scale events. The correlation between synoptic traffic rate and population density is weak ($\rho = 0.224$, $p = 0.261$) and not statistically significant at the $\alpha = 0.05$ level, unlike the relationship between lake-effect rates and population density (Figure 9). This suggests factors specific to lake-effect snow cause drivers in urban areas to cancel trips at a higher rate than drivers in rural areas. Greater intensity of lake-effect snow in the Cleveland lakeshore area may be one of these factors.

### Time of Day

Finally, the time of day at which observations were taken appears to affect the traffic rates. Figure 11 shows average traffic rate at all studied counters (regardless of the number of observations) for both lake-effect and synoptic-scale snowfall at each hour of the day. Differences between lake-effect and synoptic rates at any given hour of the day are relatively small when compared to each standard deviation. However, other patterns are noticeable. Both lake-effect and synoptic rates reach maxima during the overnight period, between 2400 and 0500. At these times, mean rates for both types of snow are near or even above 1.0, indicating that snowfall has little to no effect on traffic volume. This shows that drivers are not likely to be making cancellable trips during late-night and early-morning hours. Standard deviations in rates are high at these times because overall traffic volume is low, so any variation in volume is magnified by comparatively low denominators when calculating traffic rates.

Mean traffic rates (but not total volume) are lowest between the hours of 1000 and 1700. This finding suggests drivers take their most cancellable trips at these times. This period of time
is also when roadways tend to be most crowded, so drivers may be more cautious of compromised conditions when there are many other vehicles out at the same time. Daylight and visibility may also play a role; drivers may be more perceptive of falling snow and poor driving conditions when they can see it during the day.

![Traffic Rates by Time of Day](image.png)

Figure 11. Mean rates and standard deviations by time of day. Source: MS2.

While overall traffic volume is usually highest during the day (particularly weekday rush hours), even during poor weather, traffic rates (snow volume divided by control volume) are lowest during this time frame. Therefore, drivers are more likely to cancel a trip when there are many other vehicles on the road and an elevated risk of a multi-car accident. However, there are still many more vehicles out on the roads during the daytime, even when snow is falling. Thus,
despite increased driver awareness of poor conditions, accident risk may still be highest during the day, regardless of the type of snowfall (lake-effect or synoptic).

Accident Occurrences

This study focuses on traffic volume during snow events, but accident risk during snowy conditions provides a research motivation for this work. A brief case study provides some insight regarding the relationship between volume and accident rates. Elkhart County, Indiana (population 198,000) is in the northern part of the state and borders Michigan to the north, with metropolitan South Bend to the west (Figure 12). It is also the location of two traffic counters with sufficient observations to be included in the above statistical tests, and these counters are plotted in Figure 12.
NWS records from nearby South Bend show that lake-effect snow fell throughout the day on January 7th, 2015. The South Bend airport reported 4.9 inches of snow on the 7th, and although Elkhart County likely received a lesser total (since it is further from Lake Michigan), radar data used in this study indicate snowfall from midnight to early evening within the limits of the county. Accident data obtained from the Indiana Department of Transportation show 70
reported traffic accidents on that date in Elkhart County alone. Snowy or icy roadways were mentioned in all 70 reports, and falling or blowing snow were mentioned in 56 of 70 (80%). Figure 13 compares the time of these accidents to traffic volume at a nearby counter.

Figure 13 is a chart showing the trends of traffic volume and accident frequency in Elkhart County on January 7th. Traffic volume was recorded at a single counter on the southern side of the county (see Figure 12), and its counts were used to approximate overall traffic volume throughout the county. Figure 13 shows that traffic volume and accident frequency followed very similar trends throughout the day on the 7th, reaching minima during the late night and early morning hours and maxima during the daytime. Calculation of crash risk as accident frequency divided by overall traffic volume would yield nearly consistent rates throughout the day. This
finding suggests that increased visibility during daylight hours may in part counteract increased crash risk due to crowded roadways, although a much more thorough and focused study would be required to come to any substantial conclusions on this manner, since other factors like vehicle speed and following distance likely play a large role in crash risk.

**Summary of Findings**

Table 3 summarizes the statistical findings of this work. Although there is a trend toward lower synoptic-scale traffic rates than lake-effect rates at the 27 well-sampled counters, no difference was found at the 0.05 significance level. However, further inspection of the data reveals several intriguing patterns. Lake-effect snow is shown to have less of an effect on traffic volume at locations further from the lake shore. This is probably because lake-effect snow decreases in intensity as it moves further inland. This could mean that crash risk is higher if more vehicles are on the road during poor conditions.

<table>
<thead>
<tr>
<th>Variable 1</th>
<th>Variable 2</th>
<th>Relationship</th>
<th>Test</th>
<th>Statistic</th>
<th>Significant (α = 0.05)?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean Lake-Effect Snow Rate</td>
<td>Mean Synoptic-Scale Snow Rate</td>
<td>Difference</td>
<td>Wilcoxon Ranked-Sum Matched-Pair</td>
<td>$Z_w$ = - 1.057 ( p = 0.146 )</td>
<td>No</td>
</tr>
<tr>
<td>Rate Difference (LE rate – syn rate)</td>
<td>Distance from Lake</td>
<td>Correlation</td>
<td>Spearman’s Rank</td>
<td>$\rho = -0.53 \ p = 0.0005 $</td>
<td>Yes</td>
</tr>
<tr>
<td>Lake-Effect Snow Rate</td>
<td>Population Density</td>
<td>Correlation</td>
<td>Spearman’s Rank</td>
<td>$\rho = -0.512 \ p = 0.002 $</td>
<td>Yes</td>
</tr>
<tr>
<td>Synoptic-Scale Snow Rate</td>
<td>Population Density</td>
<td>Correlation</td>
<td>Spearman’s Rank</td>
<td>$\rho = 0.192 \ p = 0.292 $</td>
<td>No</td>
</tr>
</tbody>
</table>

Exceptions to this correlation include urban areas (particularly Akron, Ohio), where lake-effect snow rates are lower than expected given their distance from the lake. This may be
because travelers in urban areas are taking shorter, more cancellable trips, or because they have the option to take public transportation when conditions are poor. However, there is no statistical evidence for a similar correlation between population density and synoptic-scale rates. Given that lake-effect snow is more intense nearer to the lake (where more urban counters are located in northeast Ohio), it is possible that the intensity of lake-effect snow provides a confounding variable to the relationship between traffic rates and population density. Future research could seek to evenly sample traffic counters located in both urban and rural areas at varying distance from the lake to verify if there is in fact a relationship between traffic rates and population density.

Temporal analysis of traffic rates reveals that rates tend to be higher during overnight hours. Although overall volume tends to be lower at these times, fewer drivers cancel trips at late hours, as overnight trips are likely more urgent or less cancellable. Since there are fewer other vehicles on the road at these times, it is possible that drivers perceive multi-vehicle accident risk to be less, despite lower visibility when the sun is down. Accident risk is outside the scope of this work, but a single day, county-level case study suggests that crash occurrence fluctuates at a similar rate to overall traffic volume during snow events, so perhaps crash risk during snowfall is fairly uniform throughout the day. This provides another angle for future research, as time of day, type of road, setting, road maintenance, following distance, vehicle speed, age of driver, and other factors may play a role in accident risk.
CHAPTER V

CONCLUSIONS

Snowfall is known to have substantial effects on traffic flow, volume, and accident risk. This study seeks to compare the effects of lake-effect and synoptic-scale snowfall on traffic volume. The quantification of traffic volume plays an important role in determining accident risk and planning road-maintenance strategies. The localized nature of lake-effect snowfall is hypothesized to cause less of a decrease in traffic volume than synoptic-scale snow, which would indicate that lake-effect snow poses a greater crash hazard to drivers since more vehicles will be on roads during poor driving conditions. Traffic volume from 27 counters in northern Indiana and northeast Ohio was analyzed, and results show no strong statistical evidence that volume during lake-effect events is greater than volume during synoptic events. However, the relationship between lake-effect volume and synoptic-scale volume is dependent on several other factors regarding the location of the traffic counter. Counters nearest to the lakeshore were shown to exhibit lower traffic volumes, on average, during lake-effect snow than synoptic snow, likely because lake-effect snowfall is more intense nearer to the lake itself. Traffic volume during lake-effect events was also shown to be less in densely-populated areas, although this may be influenced by the location of cities in the study area very near to the lakeshore, and thus they may receive more intense lake-effect snowfall. The relationship between traffic volume during snow events and population density provides an avenue for future study.
Time of day also appears to have an influence on traffic volume, although the data is noisy and variance is high. During daytime hours, the data shows a trend towards lower traffic volume as compared to control volume. This finding suggests the possibility that more drivers cancel trips during daylight. However, during overnight hours, average volumes are much closer to control volumes, so snowfall appears to have much less of an effect on traffic at these times.

A case study of crashes on a snowy day in Elkhart County, Indiana, shows crash occurrence exhibits similar trends to volume at a nearby traffic counter. If this pattern is consistent, crash risk may be fairly uniform throughout the day. However, a study focused specifically on crash occurrences would be required to draw any statistical conclusions on this topic. Crash risk and traffic volume are surely interrelated, and future findings and applications could help improve traffic safety during adverse weather.


