Escaping the Heat: Climate Change and Visitation to the Lake Tahoe Basin

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Word Count: 6550 words text + 3 tables x 250 words (each) = 7300 words

Submitted [July 31, 2021]

ABSTRACT

The Lake Tahoe Basin of California and Nevada is a popular destination for visitors, and as temperatures in the western United States continue to rise, visitation demand is likely to grow. Increased visitation has already contributed to a rise in congestion and accidents, deterioration of air quality, and tension between residents and visitors. Policymakers are exploring ways to mitigate these issues, including a placing a limit on vehicle miles of travel (VMT) by visitors. Given this, there is a need to 1) understand how many day and overnight visitors are in the basin each day and their associated VMT, and 2) how particularly hot days in the nearby Sacramento Valley contribute to increased visitation. Using survey data collected by the Tahoe Regional Planning Agency and network GIS analysis, this study models visitor travel routes, using these to estimate their VMT. As most visitors accessed the Basin via Echo Summit and Tahoe City, using Caltrans traffic volume data, and publicly available weather data we then model the relationship between particularly hot conditions and vehicle entries at these two points. We found that for hot conditions in the Sacramento Valley, the number of vehicles that enter the basin is between 500 and 1,200 depending on approaches used to identify hot conditions. Using the VMT estimates of visitors who enter at these locations, an additional 12,000 and 33,000 VMT can be expected in the basin. This analysis helps identify the primary locations for initial interventions to mitigate travel.

Keywords: VMT estimation, Temperature Increase, Visitation, Lake Tahoe Basin

INTRODUCTION

The Lake Tahoe region along the border between California and Nevada has long been a popular travel and recreation destination. As nearby cities continue to grow and visitation demand increases, increased vehicle travel to the area creates a suite of problems for agencies, policymakers, residents, and visitors. The west is experiencing steadily rising temperatures and longer, drier summer seasons (*1*), making Lake Tahoe an even more appealing recreation destination to those living in nearby, lower-elevation cities in California and Nevada. The Lake Tahoe region's resident population has never exceeded 65,000 people but past estimates indicated that the number of visitors in the area on days of peak visitation may exceed 200,000 (*2*). Congestion and safety-related issues accompany this increase in travel, while also contributing to local air and water quality issues. Planning for high automobile use and its associated impacts is not new to Lake Tahoe, as for over 50 years, stakeholders and planners have explored ways to mitigate issues resulting from increasing vehicle usage in a region with limited alternative transportation options.

Stakeholders agree that intervention is needed to address these issues according to a final report on transportation published by the Lake Tahoe Bi-State Working Group (*3*). However, a persistent barrier to informing any relevant policy has been the lack of robust data on how many overnight and day-use visitors, full time and seasonal residents, and commuters are traveling in and around the Lake Tahoe area each day. Agencies also have limited information about where and how each group travels within the basin. Each group contributes to travel-related impacts in the region differently and competing local visions have emerged about how to tailor policy solutions accordingly. The increase in visitors has already exacerbated long-standing tensions with local residents, with day visitors a particular source of frustration (*4*).

Another key challenge is the multi-jurisdictional nature of the region. The communities around Lake Tahoe lie within five counties in two separate states, making coordination of data collection efforts with regional and jurisdiction-specific needs a constant consideration. Regional stakeholders agree, though, that reliable data on travel group volumes, their vehicle miles of travel (VMT), and travel patterns are essential to developing strategies to mitigate these issues (*5*). Reduction of VMT has been a goal in Tahoe for more than four decades and stakeholders there recently recommitted themselves to reducing reliance on the automobile and through the adoption of a new per capita VMT target. Achieving the new target requires an understanding of sources of VMT and what drives seasonal and interannual variation in regional VMT. Estimates of VMT by user group are particularly important, as the region's stakeholders are actively considering VMT limits for user groups (*5*).

Relevant VMT policy in California includes SB 375, the Sustainable Communities and Climate Protection Act of 2008 that requires regional transportation planning to identify policies that will be implemented to reduce VMT through the adoption of Sustainable Communities Strategies (SCS); and SB 743 which requires the assessment of VMT impacts from development projects within the state as a part of the environmental review process under the California Environmental Quality Act. There is still some uncertainty about how policy will be crafted to address travel-related impacts in the Lake Tahoe area, though any intervention that considers VMT of user groups must necessarily collect more precise data on how and where these groups travel. This is a priority topic to address here.

These issues are not unique to the Tahoe region; similar mountainous regions have become more desirable to visitors as temperatures increase (*6*, *7*). Past work has found that day and overnight visitors have distinct travel patterns in popular mountainous regions, and as a result, stakeholders in these regions have tried to determine exactly how many travelers of each type enter their jurisdictions when crafting policy to better address travel impacts from visitation (*8*, *9*). These data collection efforts are often difficult: most use intercept surveys (*10-12)*, though recent approaches have attempted to use location-enabled data (*13*, *14*). For Lake Tahoe, sharp increases in visitation occur during two periods of the year: 1) the winter and spring, when visitors come to enjoy the region's ski resorts and other snow sports, and 2) the summer season. In this study, we focus only on the summer season, given the relatively higher visitor volumes observed there relative to the winter and the changing climate that portends longer, drier, and warmer summers that are likely to contribute to increased visitation demand from the region's warming population centers.

Given this context, there is the need to inform policy that can mitigate the travel-related impacts of increased visitation to Lake Tahoe. Doing so involves first understanding how many visitors travel to Lake Tahoe at present and where and how they travel once there. As a result, several Tahoe stakeholders helped initiate data collection efforts to study this in recent years. Primarily, this has involved: 1) conducting a series of intercept travel surveys at numerous popular sites at Lake Tahoe, and 2) obtaining data from the private vendor StreetLight, which derives trip origin-destination data from users' devices where location data is shared. Each of these existing datasets has provided some useful information on the balance of visitor types, but how and where each group travels are less clear. In particular, there is uncertainty about how many day and overnight visitors enter the area each day through its limited number of entry points during the summer season when visitation is highest, and the VMT associated with these visitors and their trips. This is essential to understand in the context of rising temperatures that are contributing to higher visitation. It is likewise essential to understand how sharp increases in summer temperatures in the major cities within a few hours' drive to Lake Tahoe influence visitation and in turn, VMT. Of particular interest is the VMT of visitors that occurs within the geographic boundaries of the Lake Tahoe Basin, defined by the extent of the watershed that surrounds Lake Tahoe. This boundary is important, as Tahoe stakeholders can craft policy that applies to this area. Therefore, in this study, we address two primary research questions:

> What is the average VMT that occurs within the boundaries of the Lake Tahoe Basin attributable to day use visitors and overnight visitors, and how does this vary by where they enter the basin?

> What is the relationship between visitation volumes and exceptionally warm conditions in the nearby Sacramento region of California, and what are the resultant potential impacts on VMT by day and overnight visitors within the Lake Tahoe Basin as temperatures increase?

To address these questions, we organize existing datasets, estimate VMT of day and overnight visitors within the geographic boundaries of the Lake Tahoe Basin using network GIS analysis, and then model the relationship between vehicle volumes at key Tahoe Basin entry points and exceptionally warm conditions at lower elevations. Using this model and the VMT estimates of each visitor group, we can then estimate projected in-basin VMT attributable to increased visitation on future warmer days. Results from this analysis can help inform how to best tailor policy interventions in particular geographic locations or to user groups to help mitigate rising vehicle travel and its resultant impacts.

STUDY AREA

Lake Tahoe sits at approximately 6,200 feet above sea level, on the border between California and Nevada (Figure 1). Due to the mountainous topography, there are a limited number of entry points: only seven paved roadways offer access to the Lake Tahoe Basin. In 2018, nearly 1.4 million vehicles passed through Echo Summit, which is the entry point along US Highway 50 that connects greater Sacramento to South Lake Tahoe (*15*). Nearly 1.7 million entered through Tahoe City on the lake's North Shore, which is a key route that connects to Interstate 80 at Truckee and offers access to both Sacramento and Reno (and points beyond). Another 2.6 million came over Spooner Summit, a key entry point for those traveling from Reno and Carson City, Nevada. These three entry points account for 56% of average vehicle entry per day throughout the year.

Once inside the Basin, most travel occurs adjacent to Lake Tahoe along its major thoroughfares, with few alternative routes besides minor arterials that briefly parallel these main routes in the lakeside towns. This means that almost all vehicle travel within the basin is funneled onto these main roads, increasing congestion there.

FIGURE 1 Lake Tahoe Basin, including Key Points of Interest and Highway Entry Points

Most of the region's residents live in South Lake Tahoe, which is the largest city in the Tahoe Basin (population of about 22,000) and lies at the southern end of the lake. Residents and visitors alike predominantly live, stay, and travel close to the lake's shoreline, as steep terrain prevents easy access except for along the seven road entry points. There are several ski resorts located in the Basin, particularly near South Lake Tahoe, along with several parks, beaches, and marinas that surround the lake, in addition to the popular commercial districts in each lakeside town. Several major ski resorts are located south and west of Truckee, but these are primarily located outside of the Tahoe Basin.

DATA AND METHODS

We use intercept survey data collected by the Tahoe Regional Planning Agency (TRPA) to 1) estimate average day visitor and overnight visitor VMT that occurs within the geographic boundary of the Tahoe Basin during the summer of 2018, the most recent year available, and 2) estimate average day and overnight visitor VMT attributable to visitors from each key entry point to the Tahoe Basin. For the primary entry points of Echo Summit and Tahoe City we collect daily traffic count data supplied by Caltrans, which we compare against weather conditions at regional airports.

We reviewed National Household Travel Survey (NHTS) and StreetLight data for possible application to the analysis. In the former, there were too few visitor trips recorded to support representative analysis. In the latter case, the algorithm that classified trips carried far too much uncertainty to determine day or overnight visitors in the dataset. Therefore, we rely on the TRPA intercept survey data and network GIS analysis to identify day and overnight visitor trips and to estimate their in-basin VMT.

By using the geographic locations of respondent trip origins and destinations, survey sites, and the locations of other user-provided stops or travel destinations within the Tahoe Basin collected by the intercept survey, we generated estimated shortest travel time routes by day and overnight visitors. We isolated only the mileage of those routes that occurred within the Tahoe Basin to determine each user groups' average in-basin VMT. All routes were modeled using a detailed regional street network in ArcGIS 10.7.1's Network Analyst using a Python script, which was calibrated against the Google Maps API to ensure that estimated travel times were reasonable estimates. Details on route and mileage estimation for each data source and associated user group are detailed in the sections below.

TRPA survey data

Intercept surveys were collected by the Tahoe Regional Planning Agency (TRPA) over a period of 12 days in August 2018. To do so, trained field surveyors traveled to 50 popular sites throughout the Tahoe Basin that attracted visitors and residents alike, asking people to answer a series of survey questions about their travel. In total, 1,048 intercept surveys were completed, with a response rate of 63% of those approached by survey personnel who agreed to participate. Respondents self-identified if they were day visitors, overnight visitors, seasonal residents, or full-time residents. Of those identifying as visitors, 155 were day visitors and 495 overnight visitors. Most of the analysis conducted with these data has to date been used to inform reports that identify the relative volumes of each group at each site and to share summary statistics from each question with the public (*5*). See (*5*) for more details on the survey.

Key data of interest collected from the survey for this analysis include: 1) the geographic location of where the survey was completed, 2) the mode of transportation used by the respondent to reach the survey site, 3) the previous and next stops relative to the survey site within the Tahoe Basin (if any), 4) the lodging or home location (if applicable), and 5) the location of where the respondent entered the Tahoe Basin. In combination, we use these responses to model visitor travel and estimate VMT within the Tahoe Basin. Other survey data collected include: the travel purpose to the Tahoe Basin, and the length of stay (in hours) at the survey site. Demographic characteristics such as age of visitor and employment information were collected as well. While we use these data in generating our estimates, we must acknowledge that we had no influence on the survey questions asked or the survey sites chosen by the TRPA survey team.

For each user group, we used these data to estimate shortest travel time paths and associated in-basin VMT differently. We detail how we estimated routes for each group below.

Day Visitor Trips

Day visitor trips were the most straightforward to model. All respondents provided a trip origin point outside of the basin, a highway entry point, and a trip destination point that they planned to go to outside of the basin that same day. These three locations at minimum were required to estimate day visitors' travel routes. If provided, we included any additional in-basin stops prior to or after visiting the survey site by the respondent on the route to better estimate the total miles of travel. Using these locations, we modeled this shortest travel time path by sequentially ordering the stops on our detailed street network in GIS, clipping the route output to the geographic boundary of the basin to determine the mileage of that route's travel that occurred with the Tahoe Basin. We repeated this process for all survey responses where a respondent self-identified as a day visitor.

Overnight Trips

As with day visitors, we used the given trip origin, the highway entry point, and the survey point location to model in-basin travel for self-identified overnight visitors, though additional considerations were necessary. Of interest to the study are the estimated miles traveled by the respondent on a given day, which in this case required knowing both the lodging location data provided by the respondent, and if they planned to directly enter or leave the basin relative to the survey site. If they did, we estimated the route from the basin entry point to the survey site (or to the exit from the survey site), and then the associated miles to (or from) the lodging location relative to the survey site. If additional previous or next stops were provided between these points, we included them on the route. The aggregate of this trip is then the estimated daily mileage of travel for overnight visitors from the intercept survey.

If the respondent did not enter or exit the basin that day, we estimated travel between the given lodging location and the survey site and back, including any additional previous or next stops if provided. For overnight visitors, there is a limitation to estimating VMT using these data, in that the intercept survey only captures the trip on which the respondent was interviewed. It is possible that overnight visitors made additional trips that day to and from their lodging location within the Basin that went unreported by the intercept survey. Given the nature of the survey sites and the times at which responses were collected, it is reasonable to assume that these locations represented a primary destination of visitors for that day. However, the values estimated here may in fact underestimate the true daily in-basin VMT of overnight visitors, and therefore represent a conservative estimate.

We do, however, separately account for the miles of travel between the lodging location and the given entry point as "additional" miles of travel attributable to overnight visitors, understanding that those miles of travel occurred on a separate day than that of the day in which they completed the survey. We report them separately in this analysis for this reason.

Traffic Count Data

The traffic count data used in this study measures daily vehicle volumes at the seven entry/exit locations throughout the Tahoe Basin. Here, we focus on key entry points; specifically Echo Summit and Tahoe City. Since there are limited points of entry into the basin, these locations offer good estimates of the overall traffic volumes on each day.

Traffic data is available from 2011 to 2020 for Echo Summit, and from 2012 to 2020 for Tahoe City. The Tahoe City data do not include the years 2016 to 2018. For both locations, we subset the data to include only the summer months of June, July, August, and September. The data are also reduced to include only days with over 1000 vehicle trips for Echo Summit. This reduction is largely to remove days with the traffic volume recorded at zero, but also through a visual inspection of the data that shows the days with much lower volumes are likely outliers and while these days should be examined individually, they are likely to skew the results of the current analysis. Similarly, there are three days in the Echo Summit data with extremely high volumes that were removed for our analysis.

Weather Data

Weather data were downloaded from National Oceanic and Atmospheric Agency. High and low temperature measurements taken at the Sacramento International Airport are used to represent temperatures in the Sacramento area. The data were cleaned prior to finalizing temperature evaluation. First, there were a few days with temperatures over 120; since these were limited these were taken out of the data since they are outliers and have the potential skew results. Although these days are few and far between in the current data (2011 to 2021), days over 120 degrees are likely to become more common in the Sacramento area in the future (*5*).

Accounting for Background Patterns

Travel increases in the summer season irrespective of temperatures, so we calibrate our analysis to identify days or stretches of days that have higher than usual temperatures, i.e. high enough temperatures to motivate unplanned, or spur of the moment travel to escape the discomfort of the heat in the Sacramento Valley. There are several ways to address typical seasonal fluctuations in traffic that relate to seasonal weather patterns, versus those that may be described as more acute shifts in temperature that trigger increased traffic flows. We therefore represent particularly hot conditions using five distinct methods in our evaluation of the relationship between hot temperatures in the Sacramento Valley and traffic flows in the Tahoe Basin. These are:

1. High Temperature: this is the continuous measure of the high temperature recorded each day. In the summer months for the years included here this ranges from a minimum of approximately 60 degrees Fahrenheit (F) to a maximum of 110 F.
2. High Over 100: this approach uses a binary measure of whether the high temperature is over 100 degrees F. We explore the potential for these days to trigger increased traffic flows in the Tahoe Basin resulting from Valley residents escaping the hotter temperatures.

3. Heat Wave: we expand the High Over 100 degrees method to a binary measure of 2 day stretches over 100 degrees F since one hot day may be easier to tolerate than a stretch of several scorching days. The heat wave is recorded in the data on the second day with a high temperature over 100 F.
4. Night Temperature: Hotter than usual nighttime temperatures that do not provide relief from heat may be even more aggravating than hotter than usual daytime temperatures and thus contribute to a greater inclination to escape the heat. Here, we look at the recorded low temperatures on each day and identify days when the low temperature for two consecutive days does not go below 65 degrees F in a binary measure. This captures conditions that for this region represent particularly warm night conditions.
5. Above Average: this approach takes each day and compares the high temperature for the day in question to those of the surrounding week by taking the seven-day average temperature with each day at the center of the week. If the focal day is more than one standard deviation higher than the average temperature for that seven-day window, the day is considered Above Average for high temperature. This is recorded as a binary measure.

RESULTS

We first present the outcomes of initial data review, exploring the relationships between temperatures in the Sacramento Valley, and traffic volumes at Echo Summit and Tahoe City (Figure 2, Figure 3). Next, we present our estimates of VMT attributable to visitors, examining the difference between day use and overnight visitors and between different points of entry to the basin. We then present our analysis of the relationship between visitation volumes and exceptionally warm conditions in Sacramento, California.

Descriptive Statistics

Two clear patterns emerge; first, temperature is linked to increased flows, and second, weekend days (Friday and Saturday in particular) have higher flows than weekdays. These trends are evident at both points, but for Echo are more pronounced. This is likely due to Echo being a more important entry point for visitors, whereas Tahoe City may include higher volumes from commuters and possibly locals, which would not be impacted substantially by hotter temperatures in the Sacramento area. Figures 2 and 3 present these trends graphically.

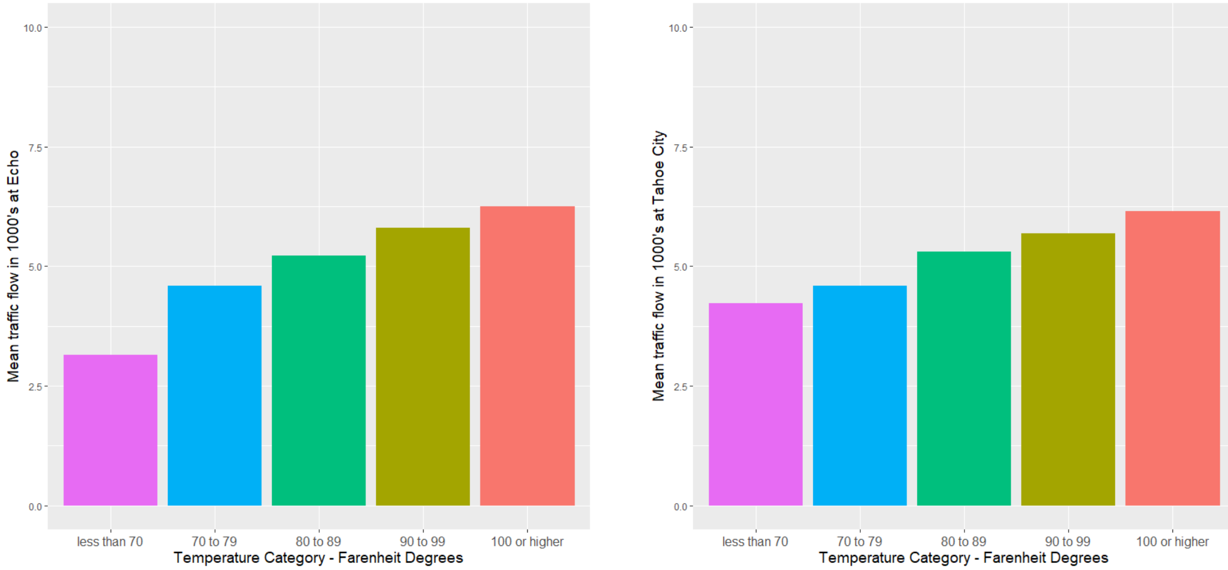

FIGURE 2 Temperature Categories and Mean Traffic Flows During Summer Months at Echo Summit and Tahoe City

The mean traffic flows by temperature category are significantly different in an analysis of variance; both result in p values less than 0.001. Similarly, when looking at the mean traffic flows on each day of the week, results are significant with $p < 0.001$ for both the Echo Summit and Tahoe City traffic count stations. These results are shown graphically in Figure 4. Peak traffic flow days are Friday and Saturday. Throughout the analysis presented here, weekend is defined as Friday and Saturday, rather than Saturday and Sunday, as we aim to control for the increased flows on these days of the week.

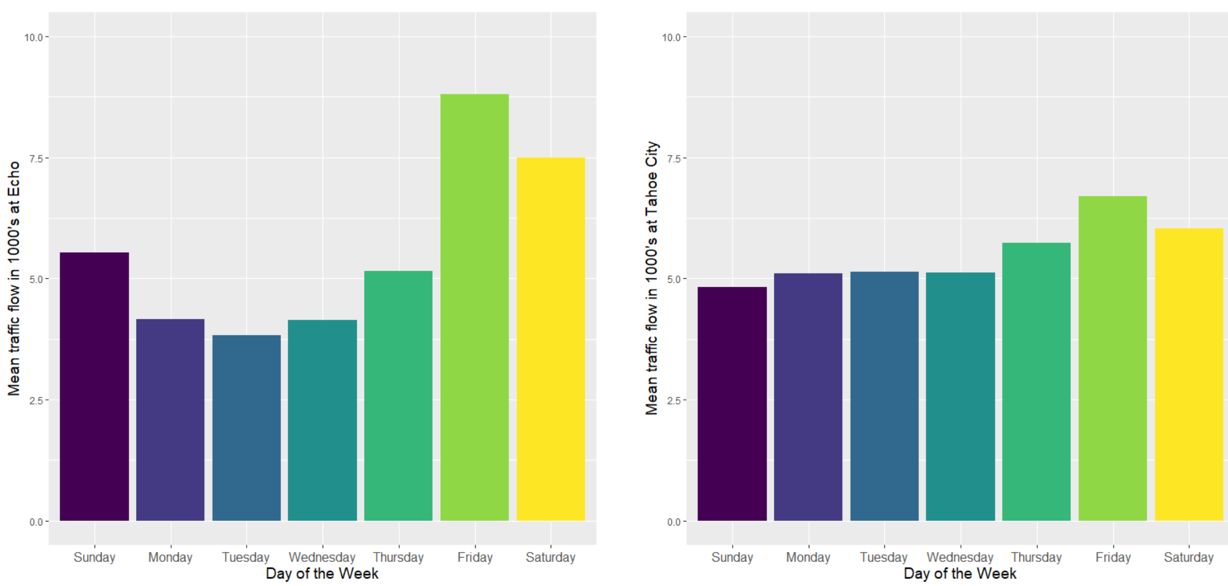

FIGURE 3 Day of the Week and Mean Traffic Flows at Echo Summit and Tahoe City

Visitor In-Basin VMT Estimates

Table 1 shows that, on average, day visitors travel 26.3 in-basin miles per day, with notable variation by entry point. For these summer visitors, 26% of the in-basin VMT from day visitors is attributable to those coming over Echo Summit, with an additional 22% via Tahoe City. Tahoe City is responsible for the most observed day visitor entries, though the in-basin VMT is higher for those entering at Echo.

Using the estimated number of total day visitors in the Lake Tahoe Basin from the Tahoe Effective Population Model (15,924) and the average vehicle occupancy reported by day visitor survey respondents (2.6 per vehicle), and the overall estimate of 26.3 miles of travel, this would translate to over 160,000 daily miles of travel attributable to day visitors.

TABLE 1 Summary Statistics for Summer Day Visitors and Overnight Visitors to the Tahoe Basin, by Entry Point.

	Day Visitors			Overnight Visitors		
ENTRY POINT	**n**	**Miles (Total)**	**Miles (Mean)**	**n**	**Miles (Total)**	**Miles (Mean)**
Brockway	12	244.3	20.4	58	997.5	17.2
Mt Rose	17	609.7	35.9	19	432.0	22.7
Spooner	41	982.9	24.0	93	1872.6	20.1
Kingsbury	11	295.0	26.8	23	481.4	20.9
Luther	0	0	0	10	178.0	17.8
Echo	30	1045.8	34.9	162	2812.5	17.4
Tahoe City	44	892.1	20.3	122	2219.4	18.2
TOTAL	**155**	**4069.8**	**26.3**	**495**	**9071.7**	**18.3**

In contrast to the day visitors, more overnight visitors enter the Tahoe basin from Echo Summit with Tahoe City being the next most popular entry point for visitors. For both visitor groups, these are the two most frequent points for visitor entry both in terms of total vehicles and VMT per day.

Using the estimated number of total overnight visitors in the Lake Tahoe Basin from the Tahoe Effective Population Model (36,418) and the average vehicle occupancy reported by overnight visitor survey respondents (3.3 per vehicle), and the overall estimate of 18.3 miles of travel, we calculate over 200,000 miles driven each day by overnight visitors. As mentioned, this is a conservative estimate of their travel, as this only reflects their in-basin trip on which they were intercepted. The total additional distance that the 495 overnight visitors would have had to travel in-basin to reach their lodging location was 9,650 miles.

Traffic-Weather Modeling

We use linear regression models to evaluate the relationship between daily fluctuations in temperature in the Sacramento area, and daily changes in traffic volumes over key entry points into the Tahoe Basin. We selected the entry points along Highway 50 at Echo Summit, and the point along Rampart Drive (corresponding to highway 89) in Tahoe City, as these two locations had the highest reported visitor numbers in the intercept survey (48% of day visitors and 57% of overnight visitors).

Here we present the outcomes of several model estimations, each using a different approach to account for the hottest days and the possible impact on travel. As noted above, we consider five formulations of temperatures to evaluate the relationship between hot days and traffic volumes in the Tahoe Basin. In each model we control for weekend travel by including this as a binary variable. We present the results of each model for Echo Summit in Table 2, and for Tahoe City in Table 3.

TABLE 2 Model Results for Echo Summit (N = 730)

Model	High Temp	High Over 100	Heat Wave	Night Temp	Above Average	Weekend Only
Number of Occurrences	NA	84	36	18	90	208
Intercept (p value)	-1.452 (0.017)	4.49 (p < 0.001)	4.538 (p < 0.001)	4.559 (p < 0.001)	4.545 (p < 0.001)	4.581 (p < 0.001)
Temperature Measure (p value)	0.066 (p < 0.001)	0.778 (p < 0.001)	0.885 (p < 0.001)	0.69 (0.042)	0.312 (0.052)	NA
Weekend (p value)	3.52 (p < 0.001)	3.563 (p < 0.001)	3.553 (p < 0.001)	3.572 (p < 0.001)	3.549 (p < 0.001)	3.558 (p < 0.001)
R-squared	0.61	0.57	0.57	0.56	0.56	0.56

TABLE 3 Model Results for Tahoe City (N = 452)

Model	High Temp	High Over 100	Heat Wave	Night Temp	Above Average	Weekend Only
Number of Occurrences	NA	45	19	8	49	125
Intercept (p value)	0.481 (0.523)	5.122 (p < 0.001)	5.173 (p < 0.001)	5.149 (p < 0.001)	5.163 (p < 0.001)	5.185 (p < 0.001)
Temperature Measure (p value)	0.052 (p < 0.001	0.663 (0.002)	0.398 (0.214)	1.466 (0.002)	0.215 (0.295)	NA
Weekend (p value)	1.149 (p < 0.001)	1.177 (p < 0.001)	1.172 (p < 0.001)	1.225 (p < 0.001)	1.185 (p < 0.001)	1.189 (p < 0.001)
R-squared	0.20	0.15	0.14	0.15	0.14	0.13

For the models at Echo and at Tahoe City, the model including temperature as a continuous variable (High Temp) has a higher R-squared value, likely due to its specification as a continuous variable. The other models use binary variables and for some, the low level of occurrence likely contributes to the weaker ability of the variable to explain much of the variation in traffic flows. Further, we see that the models for Tahoe City explain a much lower proportion of the variation in flows. As noted earlier, we attribute this outcome to the higher use of Echo Summit by visitors (both day and overnight). In other words, temperature fluctuations in the Sacramento area have less bearing on traffic flows at Tahoe City, since visitors from here are less likely to enter the basin through Tahoe City.

Interestingly, none of the models other than the High Temp model improve the R-squared value substantially over the model with only the weekend variable, despite the coefficients being statistically different from zero for all of the different formulations of high temperatures, for Echo, and for about half of the measures for Tahoe City. This result suggests that unusually high temperatures explain a limited share of the variation in traffic counts in comparison to the substantial share of variation explained by weekend days. This makes sense, given the dominance of Monday to Friday work schedules that make it difficult for many workers to head to the mountains during the week no matter how hot is gets. Similarly, for workers who are free on weekends, a trip to the mountains might be appealing even if temperatures are reasonable. These results are also confirmed by a preliminary look at models interacting the measures of temperature with a binary variable for weekend. The interaction term adds some explanatory power, but for the most part these terms are not significant predictors of traffic volume. These models are not included here, but do suggest that weekend days are especially important for increases in VMT.

Even so, temperatures do have a notable effect on traffic counts. The coefficient values for temperature variables are similar across the two locations. Note that the coefficients for continuously measured temperature are of a different magnitude than the others simply because of the difference in the type of measurement; degrees versus binary values of 0 or 1. (If the temperatures were converted to 10's of degrees the coefficients would be 0.6 and 0.5 for the Echo and Tahoe City models respectively). The coefficient values for weekend days are consistent across the models and reflect the average change in flows of traffic on weekend days versus weekdays: about 3,500 vehicles at Echo, and about 1,200 for Tahoe City. Below, we summarize the key outcomes of each model, and apply the results to the estimated VMT for day and overnight visitors for each of these two entry points. Referring to table 1, if we assume increases in traffic volumes are equally split between day and overnight visitors, on average every added vehicle at Tahoe City contributes to 19.25 in basin VMT, and every added vehicle at Echo Summit contributes to 26.15 in basin VMT.

1. High temperature: For Echo every 10-degree increase is associated with an increase in traffic volume of 660 vehicles. At the Tahoe City entry point, changes in temperature of about 10 degrees relate to an increase in traffic flow of 520 vehicles. If this additional visitation is evenly split between day and overnight, this would translate to 17,259 miles of in-basin VMT attributable to visitors for each 10 degree increase in temperature at Echo and 10,010 at Tahoe City, using the VMT estimates of each group derived from the survey.
2. High Over 100: When temperatures are over 100, compared to not, traffic counts increase by 770 vehicles at Echo and 660 vehicles at Tahoe City. This is perhaps the most important relationship, and for Tahoe City high temperature over 100 has the highest impact of any of the measures of temperature across the models estimated here.
   This would result in 20,135 additional VMT for travelers coming over Echo Summit, and an additional 12,705 for Tahoe City; a total of nearly 33,000 additional VMT each day over 100 degrees F.
3. Heat Wave: When two days in a row are over 100 degrees, traffic counts increase by 880 vehicles at Echo Summit – the highest increase for Echo Summit across the measures explored here, and 398 vehicles at Tahoe City.
   A heat wave of two days would result in an additional 23,012 VMT at Echo and 7,661 at Tahoe City, or a total increase across these two points of more than 30,000 VMT.
4. Night Temp: This model is the least reliable of all the models; and show little improvement over the model with just weekend days in both locations. The coefficient values are quite extreme, with the Echo value much smaller than the coefficients for other measures and the Tahoe City value much larger. While this measure of temperature extremes makes sense intuitively the number of occurrences make it difficult to interpret the model outcomes. Since this model is not as reliable, we do not compute the resulting VMT.

5. Above Average: This measure has the highest number of occurrences, increasing the reliability of the model estimates. However, it has the lowest level of impact in terms of the coefficient value. This is likely because the measure only considers if a focal day is much hotter than the surrounding days. We do correct for the impact of an 85-degree day among a string of 75-degree days by also requiring the above average day to be over 90 degrees. However, it seems that days over 100 are what really matter. Although an above average day will increase traffic counts at Echo by approximately 312 vehicles and at Tahoe City by approximately 215 vehicles, these numbers are much smaller than the changes resulting from other measures of temperature.

   Above average days are expected to result in a total increase in VMT of 12,300 with 8,159 attributed to Echo and 4,139 VMT to Tahoe City.

Taken together, the model results suggest that hotter temperatures in the Sacramento Valley led to higher traffic flows in the Tahoe Basin, although different measures of hot temperatures are better predictors for increased traffic flows than others. The increase in traffic flows occurs even when accounting for normal fluctuations in flows on weekends. Further, as average temperatures get higher year after year, and as extreme heat events become more likely due to Climate Change, higher traffic volumes will occur more frequently (likely up to some unknown threshold). Based on the analysis of visitor VMT, this means an increase in VMT on the magnitude of the VMT attributable to an added 500 to 1,200 vehicles on days with especially hot temperatures in the Sacramento Valley. This increase in vehicles is associated with an increase in VMT of 12,000 to 33,000 each day. While in this paper, we evaluate changes assuming an even split in visitor types, stakeholders could readily use these model outputs to evaluate scenarios of differing proportions of day and overnight visitors.

DISCUSSION AND CONCLUSIONS

The recently adopted Regional Transportation Plan (RTP) and Sustainable Community Strategy for the Tahoe Region include several strategies and projects to ease congestion and reduce VMT associated with visitor travel. This analysis provides a clearer estimate of visitor VMT and projected in-basin VMT impacts that could result from higher visitation in a warming climate. These are helpful figures in the context of some of the various interventions being proposed or considered by policymakers. One aspect of the RTP is the construction and operation of 17 mobility hubs or transit centers in various locations throughout the Tahoe area. The hubs would provide connectivity between different modes of transport and facilitate travel to/from/and within the Region in modes other than the automobile. The analysis presented here provides managers with information necessary to prioritize the rollout of these mobility hubs. For example, by placing the first “wave” of these as close as possible to the entry points at Tahoe City or Echo Summit, some of the projected additional in-basin VMT could be mitigated if people have alternatives to driving their own vehicles (*5*).

At the sub-regional scale, travel within Tahoe is planned by corridor, and sub-regional targets for reducing VMT are equally ambitious. The Highway 89 Corridor Management Plan establishes goals of reducing the impacts of peak visitor travel and achieving a mode split of 50 percent of visitors using transit or active transportation for trips that start and end within the region (*16*). Reducing some of the projected VMT identified in this study could mitigate some of these resultant issues.

Traffic volumes during the typical summer season (June-September) in Tahoe have historically been higher than volumes during the shoulder seasons (Oct, Nov, Dec, March, April and May). Climate change forecasts suggest that the temperatures that were historically characteristic of the summer season will likely be increasingly observed through the historic shoulder seasons. The expansion of the seasons of most desirable temperatures likely means the higher traffic associated with those seasons will also expand. Based on our estimates, every additional 10 degrees increases traffic flows by approximately 1,200 vehicles over the two entry points to the Basin analyzed here, and anywhere leads to approximately 27,000 of resultant daily visitor miles of travel.

While other work has speculated that increasing temperatures may lead to increased visitation to the Tahoe Region to avoid extreme heat (*17*), this study is the first to quantify the relationship between temperature increases and traffic volumes. The study provides the information necessary to predict climate and weather driven changes in visitation, that would allow the region to scale management to meet the needs of future visitors. It also provides the first formal quantification of the challenges that residents and visitors may face in the decades to come. In this study, we were limited by the available existing datasets, though future data collections efforts tailored towards visitors and their travel patterns should be prioritized. Another topic to consider for future work is how relatively poor air quality, often brought about by forest fires, influences visitation, especially as fire impacts are likely to worsen in the region's warming and drying climate.

ACKNOWLEDGMENTS

This work was funded by the Tahoe Science Advisory Council through a generous grant from the Nevada Division of State Lands.

AUTHOR CONTRIBUTIONS

The authors confirm contribution to the paper as follows: study conception and design: T. Hui, S. Pike, S. Kelley, S. Handy, D. Segan, R. Haefer; data collection: T. Hui, S. Pike, S. Kelley, S. Handy, D. Segan, R. Haefer; analysis and interpretation of results: T. Hui, S. Pike, S. Kelley, S. Handy, D. Segan, R. Haefer; Author; draft manuscript preparation: T. Hui, S. Pike, S. Kelley, S. Handy, D. Segan, R. Haefer All authors reviewed the results and approved the final version of the manuscript.

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