MOUNTAIN-PLAINS CONSORTIUM

MPC 19-376 | W.E. Marshall, Y. Golombek, N. Coppola and B. Janson

The Unresolved Relationship between Street Trees and Road Safety

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July 2019

Acknowledgments

The authors extend their gratitude to the Mountain-Plains Consortium, the U.S. Department of Transportation, the Research and Innovative Technology Administration, and the University of Colorado Denver for funding this research. We also would like to thank Austin Troy and Matt Cross for their assistance with this work.

Disclaimer

ABSTRACT

The roadside area where fixed-object hazards are explicitly minimized is called the clear zone, which became standard design practice soon after the 1966 Congressional hearings on road and automobile safety. Mounting evidence, however, is beginning to cast doubt on what we think we know about the impact of roadside clear zones on actual safety outcomes. This is particularly an issue with street trees in urban contexts, which are known to provide economic, environmental, and livability benefits, but are also widely considered a road safety detriment.

Part 1 relies on advances in remote sensing to map both tree canopy and street-tree locations in GIS for the entirety of the city and county of Denver, Colorado. We then statistically test the association between street trees and seven years of road safety outcomes while controlling for factors known to be associated with crash outcomes. Despite 50 years as standard design practice, our results suggest that the expected safety benefit of roadside clear zones – at least with respect to street trees in an urban context – may be overstated. In fact, larger tree canopies that extend over the street are associated with fewer injury/fatal crashes, as well as fewer crashes overall while holding all other variables constant. The number of street trees per mile associates with improved safety in wealthier neighborhoods, but it can be detrimental in low-income neighborhoods. This inconsistency represents an equity issue in need of future research. When assessing the safety impact of street trees in the clear zone, municipalities and transportation agencies need to be more cognizant of context and the potential influence of street design changes to road user behaviors, particularly related to issues that more directly affect safety, such as travel speeds and driver awareness.

Part 2 investigates the usefulness of 3D volumetric pixels (voxels) and USGS Quality Level 2 (QL2) LiDAR data to measure features in streetscapes. As the USGS embarks on a national LiDAR database with the goal of covering the entire United States with QL2 data or better, this paper investigates uses of QL2 LiDAR for the 3D measuring of streetscapes. Tree mapping is a common use of QL2 LiDAR data, and street trees are among the most common features within urban streetscapes that transportation and urban designers assess. Traditional remote sensing techniques derive tree polygons from imagery; and traditional uses of LiDAR for tree canopy mapping are based on deriving a 2D canopy polygon with an attribute for elevation height. However, when breaking up streetscapes into 5-ft elevation zones and calculating street-tree voxels at each elevation zone height, 3D characteristics of street trees that become prevalent completely differ from the common 2D LiDAR derived street trees. Statistical tests in this paper display how different the 3D characteristics are from the 2D-derived LiDAR polygons, as this paper introduces a new methodology for measuring streetscape features in 3D, particularly street trees.

The appendices include examples of how these issues were integrated into assignments for graduate level civil engineering classes, as well as the output from a foundational master’s report.

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PART 1: URBAN CLEAR ZONES, STREET TREES, AND ROAD SAFETY[1]

1. INTRODUCTION

One of the hallmarks of the road safety program in the United States over the last half century is the clear zone concept. The "clear zone" refers to the roadside area where engineers minimize "fixed-object hazards," such as trees, utility poles, and signs, in an effort to improve safety outcomes. The concept began to proliferate in transportation engineering circles after the 1966 Congressional road safety hearings. While Ralph Nader and his book, Unsafe at Any Speed, about automobile design practices garnered much of the attention, the testimony of General Motors (GM) engineer Ken Stonex ended up influencing road design standards just as much (Weingroff, 2003). Stonex worked at the GM Proving Ground, a 65-mile test-track facility in Milford, Michigan, and spoke to Congress about the fact that limited-access highways are far safer on a per-mile basis than other street types. His research suggested three keys to better road safety: access management, one-way traffic, and fewer roadside obstacles. Focusing on the last point, Stonex reported that removing all fixed objects from within 100 feet of the road, such as at the Proving Grounds, would make it "pretty hard to commit suicide on" (Weingroff, 2003). Stonex went on to say:

> This is the real transportation problem that remains to be approached. What we must do is to operate the 90% or more of our surface streets just as we do our freeways… [converting] the surface highway and street network to freeway and Proving Ground road and roadside conditions (Dumbaugh & Gattis, 2005; Weingroff, 2003).

The American Association of State Highway Officials (AASHO[2]) quickly put this idea into standard road design practice with the publication of its 1967 manual, Highway Design and Operational Practices Related to Highway Safety, which cited the need for a 6-meter (19.7') clear zone. AASHO soon increased the clear zone distance to 9 meters (29.7') and began recommending application in urban locations as well as rural. The 2011 AASHTO Roadside Deign Guide continues to encourage clear zone application wherever practical, although it does acknowledge that urban right-of-ways may be more restricted (AASHTO, 2011; FHWA, 2006).

Despite 50 years of standard design practice, the research remains conflicted over the true association between the clear zone and road safety. This is particularly an issue when it comes to street trees in an urban context. The research points to street trees improving the pedestrian environment, reducing urban heat island effects and the need for as much drainage infrastructure, as well as a host of other social, environmental, and economic benefits (Burden, 2006; Ewing & Dumbaugh, 2009). In his research on livable streets, Donald Appleyard discusses how trees "provide relief from the hardness and grayness of the city" and help "provide shade in the summer and remind people of the natural environment, which is often far away; they signal the seasons, and symbolize, through growth, flowering and decay, the cycles of life itself" (Appleyard, 1980). Street trees seem to be beneficial in most every way but one: road safety. While traffic engineers acknowledge that trees can be an asset, they also point out that trees are the "single most commonly struck objects in serious roadside crashes" (FHWA, 2006). For instance,

[1] This portion of the report has been peer-reviewed and published: Marshall, W., Coppola, N., and Golombek, Y. Urban Clear Zones, Street Trees, and Road Safety. *Research in Transportation Business & Management*, Vol. 29: 136-143, 2018 (doi.org/10.1016/j.rtbm.2018.09.003).

[2] In 1973, AASHO changed its name to AASHTO, the American Association of State Highway and Transportation Officials, which it remains known as today.

national safety data suggest that car/tree collisions account for more than 4,000 fatalities and 100,000 injuries in the U.S. each year.

This section seeks to better understand these safety-related issues via a study of seven years of crash data from Denver, Colorado, which we chose due to the ability to map both tree canopy and street-tree locations in GIS. The next part of this section delves into the existing research on street trees and road safety outcomes, which is followed by an in-depth discussion of our data and methods. Controlling for variables shown to be associated with crash outcomes – such as street-level characteristics, traffic exposure, and neighboring populations – we statistically test the association between street trees and road safety outcomes. We then consider the results in the context of behavioral changes that may occur with and without the presence of fixed-object hazards in the roadside. The section concludes with an examination of the business management implications, particularly for municipalities and transportation agencies, with respect to the design and planning of our future transportation systems.

2. LITERATURE REVIEW

Two of the early and more well-known studies on the topic of trees and road safety include a statewide study of Michigan by Zeigler and a study of Huntsville, Alabama, by Turner and Mansfield (Turner & Mansfield, 1989; Zeigler, 1986). One issue with these early studies is that they tend to focus on descriptive statistics. For instance, Zeigler found that car/tree crashes represent 2.8% of all crashes but 9% of fatalities (with most fatal crashes occurring with trees larger than 20-in. caliper) (Zeigler, 1986). He went on to show that 85% of car/tree collisions occurred within 30 feet of the roadway, a number that supported the clear zone recommendation, and cited this type of crash risk as an issue in both rural and urban settings (Zeigler, 1986). Turner and Mansfield intended to focus on the issue of urban car/tree crashes and found that 80% of car/tree crashes occurred within 20 feet of the roadway, and that most of those were with trees of 12-in. caliper or more (Turner and Mansfield 1989). These facts, however, merely describe where car/tree collisions tend to occur and/or how big the offending trees tend to be; they do not tell us anything about whether the presence of the trees themselves are associated with better or worse safety outcomes. Moreover, these studies do not consider whether we would expect fewer crashes in the first place – or perhaps even fewer severe injury or fatal crashes – with more or bigger street trees. Nevertheless, in the case of Turner and Mansfield, the authors identify a 4% reduction in crashes for every extra foot of clear zone and proceed to idealize a transportation system where every road could conform to clear zone policy (Turner & Mansfield, 1989).

One of the overarching issues for researchers trying to improve upon these studies relates to the difficulty of collecting adequate tree data at a large scale. Instead of solving this problem, the next set of studies generally looked at small analysis zones. Based on five arterials in Toronto, for instance, Naderi found that mid-block crashes dropped between 5% and 20% with trees or concrete planters located street-side (Naderi, 2003). Dumbaugh and Gattis' well-regarded 2005 paper, Safe Streets, Livable Streets, focused on two stretches of the same corridor in Orlando, Florida. Accounting for traffic exposure, he found that the more "livable" section – with trees and other fixed-object hazards placed well within the clear zone – experienced fewer crashes across all severity levels (Dumbaugh & Gattis, 2005). In a before-and-after Texas study of 10 urban arterials, Mok et al. found that the increased presence of landscaping and street trees was significantly associated with a decreased crash rate (Mok, Landphair, & Naderi, 2006). Although these studies from the early 2000s place their suspicions on conventional clear zone wisdom, Wolf and Bratton dug into the issue of car/tree collisions and concluded that urban car/tree crashes were still not well understood (Wolf & Bratton, 2006).

Recent developments in remote sensing and GIS mapping have made collecting tree canopy and/or point-level tree data a more realistic undertaking. An excellent study by Harvey and Aultman-Hall, for example, relied on the New York City open data web portal to develop streetscape measurements in GIS (Harvey & Aultman-Hall, 2015). Logistic regression models suggest that more open streetscapes – with wider roadside clear zones – were more likely to result in injury or fatal crashes. Alternatively, "crashes on streetscapes fully covered by tree canopy are 51% less likely to result in injury or death than those on streetscapes without trees" (Harvey & Aultman-Hall, 2015). Although this study only accounted for tree canopy coverage and not tree counts, and 100% tree canopy coverage is not easy to achieve, Harvey and Aultman-Hall conclude that planting street trees in urban areas should be considered a beneficial safety countermeasure. We look to build upon these advancements in remotely sensed GIS data with a study that considers both the presence of a tree canopy as well as point-level tree location data.

3. DATA

Assessing the relationship between street trees and road safety requires data on trees near roadways. As recently as five years ago, tree data at the city scale were almost unheard of, but several major U.S. cities now have programs that systematically map trees across a city in GIS. Denver was selected for this study because it is one of the only cities with both tree canopy and point-level tree data available. Another advantage of Denver is that the Denver Regional Council of Governments (DRCOG), the metropolitan planning organization for Denver, recently completed an aerial photography project that produced planimetric data in the form of edge of pavement polygons. We also collected crash data, exposure data in the form of traffic counts, and socio-demographic/socio-economic data from the American Community Survey (ACS). This section describes these data in more detail.

3.1 Tree Data

We acquired tree canopy data from the City and County of Denver open data catalog. Based on QuickBird 2-ft pixel satellite imagery from 2006, the GIS polygon delineations were created using automated feature extraction from the near infrared band.

The Denver Parks and Recreation Department collects point-level GIS tree data for all trees maintained by the city. This inventory includes all trees located along streets, in medians, as well as those in parks. While the attribute data include species and caliper range, these data remains incomplete, but will be a useful addition in future research.

3.2 Crash Data

In order to overlap with the tree canopy data timeframe, we gathered crash data for 2004 through 2010. After geocoding these data, we disaggregated the data by crash severity, mode (i.e., car, pedestrian, bike), and crash location (intersection or segment crash).

3.3 Street Data

We collected street data from multiple sources, including the city and open streets map. From these data sources, we aggregated centerline polylines, functional classification, number of travel lanes, speed limit, as well as whether or not the street has a median. Our team collected traffic counts from three sources: the Colorado Department of Transportation, DRCOG, and the City and County of Denver. We merged these data in GIS in order to account for traffic exposure in the statistical crash models.

Rather than assuming street widths based on the number of travel lanes, we were able to use edge of pavement GIS polygons, which were created using aerial imagery as part of the Denver Regional Aerial Photography Project (DRAPP) facilitated by DRCOG. This GIS layer provides the edge of pavement information for all roadways in Denver. DRCOG collected these data based upon 1"=100' scale, 4-band RGB-Ir color orthoimagery using Leica ADS40 and ADS80 digital sensors and processed it with Leica XPro software. For the purposes of this study, the planimetric edge of pavement data offered a much more accurate representation of the primary surface of all roadways being evaluated, as well as where the pavement is located in relation to the trees and tree canopy.

3.4 Socio-demographic and Socioeconomic Data

To account for socio-demographic and socioeconomic differences in income, race/ethnicity, and age, we collected block group level data from the ACS. To best match the tree and crash data, we focused on the five-year ACS sample for 2006–2010. The data included age information most likely to be associated with crash outcomes (percent of residents less than 18 years old and percent of residents greater than 65 years old). As race/ethnicity has proven to be significantly associated with crash outcomes (Braver, 2003; Campos-Outcalt, Bay, Dellapena, & Cota, 2003; Mayrose & Jehle, 2002; McAndrews, Beyer, Guse, & Layde, 2013), we collected relevant variables. These variables turned out to be highly correlated with one another, so we aggregated them into a variable representing the percent of non-white residents. For level of education, we aggregated the data into an education index score. Scores ranged from zero to two in terms of the highest level of education received, as follows: less than a high school diploma=0; high school degree or some college=1; bachelor's degree or higher=2. Thus, a score of 2.0 indicates that the average adult level of education for the specified area is at least a bachelor's degree. We also collected median household income data. The next section describes the GIS and statistical methodologies.

4. METHODS

4.1 GIS Methodology

The unit of analysis for this study is the street corridor. However, we did not want important street-level characteristics to vary along a single corridor. As a result, we derived the individual street corridors by dissolving the street layer by street name, the number of travel lanes, the speed limit, and the presence of a median. This ensured that these particular variables remained consistent along each street corridor.

Since we also needed to account for traffic exposure with each street corridor, we joined the traffic count data and focused on street segments with valid counts. We then manually assessed the resulting corridors and removed sections where the traffic count was likely to vary considerably along a single corridor (such as when a segment intersected with limited-access highway on- and off-ramps). The result was 616 street segments covering nearly 500 total street miles. Since traffic counts tend to be collected on collector or arterial roads, our sample possessed relatively few local roads.

Using the planimetric edge of pavement data, we derived polygon streets from the street centerline segments created in the last step. This facilitated the ability to calculate the percent of the street pavement covered by tree canopy. Figure 4.1 depicts our tree data clipped to the pavement polygon. The light grey represents streets without traffic counts, while the dark grey depicts two examples of street corridors included in the study. The green represents the tree canopy, while the yellow identifies the portion of the tree canopy that overlaps with the street corridors. For each street corridor, we calculated the percentage of the pavement covered by tree canopy. The trees are the points in the image. We calculated the number of street trees adjacent to each segment as well as the average distance of these trees to the pavement.

Figure 4.1 ... Tree Canopy Overlap with Street Segments

Next, we used spatial joins to count crashes along each street corridor. We counted total crashes, injury crashes, and fatal crashes. Crashes were disaggregated into either intersection-related or segment crashes.

Block-group level ACS data for the neighborhoods surrounding our street corridors was spatially joined to the street corridor polygon layer. In cases where multiple block groups corresponded to a single street corridor, we calculated a population-weighted average of each variable. For instance if 100 residents of one block group had a mean age of 60, and 20 residents of a neighboring block group had a mean age of 30, then the block group with more residents would carry more weight. In this case, the population-weighted mean age would be 55 years old. The same process was repeated for each of the ACS variables described in the data section. Table 4.1 presents descriptive statistics for our data.

Table 4.1 Descriptive Statistics (selected variables)

	Variable	Mean	SD	Min	Max
N=616 Street Segments					
Crash Outcomes	Total Crashes per Mile	481.16	879.81	0	11,286
	Injury or Fatality Crashes per Mile	63.20	110.21	0	1,215
	Total Segment Crashes per Mile	144.91	246.20	0	2,730
	Injury or Fatality Segment Crashes per Mile	14.78	21.64	0	224
Tree-Related Variables	Tree Canopy (percent street coverage)	5.90	8.04	0	57.2
	# of Street Trees per Mile	96.52	77.40	0	406.2
	Average Distance from Tree to Pavement	8.83	5.75	0	29.7
	Standard Deviation of Tree Distances to Pavement	5.16	2.95	0	18.1
Street Variables	Traffic Volumes (in thousands)	15.15	15.26	0.17	101.88
	# of Travel Lanes (average)	2.71	1.09	1	6
	Speed Limit (average)	30.15	5.26	25	45
	Presence of Median (0, 1)	0.25	0.43	0	1
ACS Variables	% Non-White Residents	42.62	25.06	0	97.90
	% of Residents Less than 18 Years of Age	18.74	10.46	0	49.90
	% of Residents Greater than 65 Years of Age	10.85	7.38	0	46.17
	Level of Education Score	1.27	0.35	0	1.98
	Household Income (average in 100,000s)	6.35	2.17	0	15.17
	Street Segment Length (average in miles)	0.79	0.77	0.03	4.42

4.2 Statistical Methodology

The question we are trying to answer is the following: how are roadside trees associated with road safety outcomes? The dependent response variable used to address this question in our statistical analysis is a count of the number of crashes. A conventional linear regression model may not be appropriate for this analysis because of the requirement that the dependent response variable be normally distributed (Long, 1997). To resolve this issue, researchers often rely upon a generalized linear model (GLM) for analyzing count-based crash data. A GLM can be used to account for a non-normal distribution using a link function that relates the linear portion of the model to the mean of the dependent response variable. Link functions can take various forms – such as log, logit, inverse, or inverse squared – but the purpose is to allow the response variable to relate to the explanatory variables in a nonlinear way (Long, 1997).

Since crash data are over-dispersed and not normally distributed, the negative binomial model is more appropriate, as it is a generalized version of the Poisson model that accounts for this over-dispersion by introducing a random stochastic component to the log-linear Poisson mean function relationship (Long 1997, Noland & Quddus, 2004). The following is the negative binomial generalized linear regression model:

$$\ln \tilde{\mu}_i = X_i\beta + \varepsilon_i$$

where:

μ_i = Randomized version of conditional mean of expected crash count of street i
X_i = Independent predictor variables
β = Estimated vector of coefficients representing effects of the covariates
ε_i = Stochastic component representing random error used to account for over-dispersion

Over the last decade, the negative binomial model has become accepted practice for traffic safety researchers conducting statistical testing of crash counts where over-dispersion is an issue (Zhou, Ivan, & Sadek, 2009). The negative binomial probability distribution is determined by (Long, 1997):

$$P(y_i|x_i) = \frac{\Gamma(y_i + \nu_i)}{y_i!\Gamma(\nu_i)} \left(\frac{\nu_i}{\nu_i + \mu_i}\right)^{\nu_i} \left(\frac{\mu_i}{\nu_i + \mu_i}\right)^{y_i}$$

where:

Γ = Gamma distribution function
ν_i = Gamma distribution parameter that affects the shape of the distribution
y_i = Crash count of Census Block Group i

The variance of the negative binomial distribution is (Long, 1997):

$$Var(y_i|x_i) = \mu_i \left(1 + \frac{\mu_i}{\nu_i}\right)$$

If α, the dispersion parameter, begins to approach zero, then a Poisson becomes the appropriate model. The dispersion parameter is related to the gamma distribution parameter as follows (Long, 1997):

$$\nu_i = \alpha\text{-}1 \qquad \text{for } \alpha > 0$$

Using negative binomial generalized linear regression, we built expected crash models by crash severity type. Fortunately for the people of Denver, there were not enough fatal crashes to conduct a statistically significant analysis, so we combined the injury crashes with the fatal crashes. In the next section, we present results for the following four statistical models:

Model No.	Dependent Variable
1	All Crashes
2	All Injury & Fatality Crashes
3	Total Segment-Related Crashes
4	Segment-Realted Injury & Fatality Crashes

The first two models include both segment-related and intersection crashes. Since clear zone work typically focuses on the roadside area along a road segment, the second pair of models assesses only segment-related crashes.

Some of the variables described in the data section ended up being highly correlated with one another, and we could not include such highly correlated variables in the statistical models due to the potential for multicollinearity issues. For instance, traffic volume and the number of lanes resulted in a Pearson correlation coefficient of 0.55; household income and the education score variable had a Pearson correlation coefficient of 0.73. Thus, final variable selections were made based on overall model strength. We also tested interaction variables to see, for instance, if the influence of the tree-related variables made more of a difference in low- or high-income neighborhoods, or in neighborhoods with a greater percentage of older residents. The results follow in the next section.

5. RESULTS

Relatively consistent trends emerged in the results of our statistical models. The percent of tree canopy coverage was significant and negatively associated with crashes in all four models. Simply put, increased tree canopy coverage was significantly associated with fewer crashes. This was the case when looking at both total crashes and segment-related crashes, as well as when considering all crash severities or those that resulted in an injury or fatality. Table 5.1 presents the results of the four statistical models. To improve clarity, we also calculated expected change in crashes per year based on changing a single independent variable and holding all other variables at their mean value for the dataset. These results are shown in Table 5.2. For example, in the top row with Model 1, Table 5.2 suggests that if the percent of tree canopy over the street decreased from a reference value of 10% to 0%, then this would be associated with an expected increase in total crashes of 24.5% (from 50.1 per year to 62.3). The reference values were selected to be close to the mean for the dataset, while the levels represent either standard deviations of these variables or logical distinctions. This expected difference in crash outcomes shown in Table 5.2 is mathematically the same as elasticity values but easier to visualize and understand (Marshall & Garrick, 2011; Noland & Quddus, 2004). With respect to the tree canopy coverage results, Table 5.1 suggests that we would expect relatively drastic reductions in crashes in all four of our models, with all other variables being held at their mean, for streets with higher levels of tree canopy coverage. For streets with 50% tree canopy coverage – as compared with the reference value of 10% tree canopy coverage – we would expect 58% fewer total crashes, 64% fewer injury and fatal crashes, 54% fewer segment crashes, and 50% fewer segment-related injury and fatal crashes. It is important to note that these results do not imply causality.

The number of trees per mile was not a significant variable in either of the road segment models, which suggests the prevalence of trees does not play a significant role in the segment crash disparities in our dataset. This variable was, however, significant and negatively associated with fewer crashes in both of the first two models that account for intersection crashes as well. However, interpreting the results is more complicated because of an interaction with household income. To better understand this interaction, we created the matrix shown in Figure 5.1. The nine squares depicted in the matrix represent one of nine combinations of household income and trees per mile. Each of those variables (i.e., household income and trees per mile) is being tested across three levels. For household income, we tested $40,000, $60,000 and $80,000. For trees per mile, we tested 25, 100, and 175; these tree numbers roughly correspond to one tree on both sides of the road every 400, 100, and 60 feet[3]. Thus, the bottom left box represents lowest household income and lowest number of trees (i.e., $40,000 household income and 25 trees per mile); the top right box represents the highest income and the highest number of trees (i.e., $80,000 household income and 175 trees per mile). The center box (i.e., $60,000 household income and 100 trees per mile) is the reference from which the percent changes shown in the other boxes are calculated. For instance, the top right box suggests that streets with the higher level of trees per mile – that are also located within wealthier neighborhoods – are associated with 20.8% fewer total crashes and 27.4% fewer injury and fatal crashes. What is interesting about these results is that higher levels of trees per mile is associated with better safety outcomes in wealthier neighborhoods, but worse safety outcomes in lower-income neighborhoods. This suggests that these factors may be a proxy for other unmeasured differences between neighborhoods of varied incomes. They may also relate to differences between lower- and higher-income neighborhoods in terms of the trees themselves. In our Denver dataset, for instance, the streets located in the poorest quartile of neighborhoods averaged less than 3% tree canopy coverage; this percent of tree canopy coverage increases with every income quartile and reaches an average of 8.4% tree canopy coverage for the streets located in the highest income quartile. It is possible that the number of trees per mile may be associated with different outcomes in lower- and higher-income neighborhoods, as

[3] Please note that we tested the overall roadside prevalence of trees, as well as the average distance of the tree from the street, but not tree spacing along the street in this analysis.

larger trees have been shown to be common in wealthier neighborhoods (Burden, 2006; Das, 1979). Our metric of trees per mile cannot capture such differences, so it would be good to see this issue receive further study once the tree caliper data catch up with the other tree-related data.

The average distance from the pavement to the centroid of the street trees for each street was significant in the first three models and associated with fewer crashes. As shown in Table 5.2, approximately 4 feet more in average distance is associated with between 5% and 7% more crashes, all other things held equal. This variable is not significant for segment-related injury and fatal crashes. Also, since these average tree distances relate to the estimated centroid of the tree and do not account for tree size, we cannot yet determine actual distance from the pavement edge to the edge of the tree. This also is an area for future research.

As expected, our traffic volume exposure metric was significantly and positively associated with crashes in all four models (i.e., more cars equal more crashes). The speed limit factor was also significant and positively associated with crashes in all four models; this result supports the existing literature suggesting “that the relationship between speed and road safety is causal, not just statistical” (Elvik, 2005). In our models, the interaction of traffic volume and speed limit was also significant. The results suggest that while higher traffic volumes and higher speed limits are both associated with more crashes, the combination of the two moderates poor safety outcomes, at least to some extent (akin to a safety in numbers effect). Our other street design variable, the presence of a landscaped median, was significant in all four models. Table 5.2 shows that streets with a landscaped median were associated with approximately 38% fewer crashes in Models 1 and 2 and 48% fewer crashes in Models 3 and 4. With respect to road safety, landscaped medians help separate opposing traffic and limit opportunities for head-on collisions, while also controlling and restricting left-turning traffic. They have also proven to be useful as pedestrian refuge areas when designed with sidewalks and curb-cuts.

Two of our socio-demographic control variables were significant in all models: the age variable representing the percentage of residents older than 65, and the race/ethnicity variable characterizing the percentage of non-white residents in a neighborhood. In both cases, higher percentages (of older or non-white residents) were associated with fewer crashes across all four models. That is, streets in neighborhoods with more older or non-white residents had fewer crashes, all other variables held equal. The variable measuring the percentage of residents less than 18 years of age was not significant in any model. Our education score variable was significant in most models, but it was also highly correlated with the household income variable, which led to stronger overall models and was the variable selected for the final models presented.

Median Household	25 Trees per Mile		100 Trees per Mile		175 Trees per Mile		
$80k	36.9	-36.7%	41.3	-29.2%	46.2	-20.8%	*Model 1: Total Crashes*
	4.6	-38.4%	5.0	-33.1%	5.4	-27.4%	*Model 2: Injury & Fatal Crashes*
$60k	57.0	-2.2%	58.3	-	59.6	2.3%	*Model 1: Total Crashes*
	7.5	0.8%	7.4	-	7.4	-0.7%	*Model 2: Injury & Fatal Crashes*
$40k	88.1	51.1%	82.3	41.3%	76.9	32.0%	*Model 1: Total Crashes*
	12.3	64.8%	11.1	49.5%	10.1	35.6%	*Model 2: Injury & Fatal Crashes*

Figure 5.1 Expected Change in Annual Crashes per Mile based on Interaction of Median Household Income and the Number of Street Trees per Mile

Table 5.1 Negative Binomial Generalized Linear Regression Crash Models

Variables	Model 1: All Crashes		Model 2: Injury & Fatal Crashes		Model 3: Segment Crashes		Model 4: Injury & Fatal Segment Crashes	
Intercept	6.2881	***	4.0584	***	5.6237	***	2.3632	***
Tree Canopy (percent street coverage)	- 0.0219	**	- 0.0206	**	- 0.0154	**	- 0.0139	**
# of Street Trees per Mile	- 0.0033	**	- 0.0037	**	- 0.0012		- 0.0023	
Average Distance from Pavement to Street Tree	- 0.0146	**	- 0.0180	**	- 0.0149	**	- 0.0061	
Traffic Volumes (in thousands)	0.1988	***	0.1929	***	0.1623	***	0.1571	***
Speed Limit	0.0490	**	0.0596	***	0.0249	**	0.0488	**
Presence of Median (0, 1)	- 0.4718	***	- 0.4991	***	- 0.6566	***	- 0.6565	***
% of Residents Greater than 65 Years of Age	- 0.0195	**	- 0.0123	*	- 0.0230	***	- 0.0121	*
% Non-White Residents	- 0.0199	***	- 0.0175	***	- 0.0179	***	- 0.0130	***
Household Income (average in 100,000s)	- 0.2327	***	- 0.2611	***	- 0.1871	***	- 0.1743	***
Interaction Variables								
(# of Street Trees per Mile) x (Household Income)	0.0006	**	0.0006	**	0.0003		0.0002	
(Traffic Volumes) x (Speed Limit)	- 0.0043	***	- 0.0043	***	- 0.0033	***	- 0.0033	***
Dispersion Parameter	0.8986		0.8896		0.8271		0.9257	
Model Fit								
Observations	616		616		616		616	
AIC	8,360		5,902		6,965		4,263	

* p <.10; ** p < .05; *** p< .01

Table 5.2 Expected Change in Annual Crashes per Mile

	Model 1		Model 2		Model 3		Model 4	
	Total Crashes		Injury & Fatal Crashes		Segment Crashes		Injury & Fatal Segment Crashes	
Base Expected Crash Counts per Mile per Year (calculated using mean values for all variables)	54.8	% Change	6.9	% Change	17.5	% Change	1.8	% Change
Tree Canopy (percent street coverage)								
0%	**62.3**	24.5%	**7.8**	22.9%	**19.1**	16.6%	**1.9**	14.9%
10% (reference value)	**50.1**	-	**6.4**	-	**16.4**	-	**1.7**	-
20%	**40.2**	-19.7%	**5.2**	-18.6%	**14.1**	-14.3%	**1.5**	-13.0%
30%	**32.3**	-35.5%	**4.2**	-33.8%	**12.1**	-26.5%	**1.3**	-24.3%
40%	**26.0**	-48.2%	**3.4**	-46.1%	**10.3**	-37.0%	**1.1**	-34.1%
50%	**20.8**	-58.4%	**2.8**	-56.1%	**8.9**	-46.0%	**1.0**	-42.7%
60%	**16.7**	-66.5%	**2.3**	-64.3%	**7.6**	-53.7%	**0.8**	-50.1%
Avg. Distance from Pavement to Street Tree								
4'	**142.8**	6.0%	**21.2**	7.5%	**41.9**	6.1%	**-**	-
8' (reference value)	**134.7**	-	**19.7**	-	**39.5**	-	**-**	-
12'	**127.1**	-5.7%	**18.4**	-6.9%	**37.2**	-5.8%	**-**	-
Presence of Median								
No Median (reference value)	**149.7**	-	**22.0**	-	**46.0**	-	**4.6**	-
Median	**93.4**	-37.6%	**13.4**	-39.3%	**23.9**	-48.1%	**2.4**	-48.1%
Age: % of Residents Greater than 65 Years of Age								
5%	**149.2**	10.2%	**20.9**	6.3%	**44.7**	12.2%	**4.2**	6.2%
10% (reference value)	**135.3**	-	**19.7**	-	**39.8**	-	**3.9**	-
15%	**122.7**	-9.3%	**18.5**	-6.0%	**35.5**	-10.9%	**3.7**	-5.9%
% of Non-White Residents								
30%	**171.1**	22.0%	**24.3**	19.1%	**48.9**	19.6%	**4.6**	13.9%
40% (reference value)	**140.2**	-	**20.4**	-	**40.9**	-	**4.0**	-
50%	**114.9**	-18.0%	**17.1**	-16.1%	**34.2**	-16.4%	**3.5**	-12.2%

6. CONCLUSION

Although we cannot generalize beyond Denver, the results suggest that – at least with respect to street trees in urban areas – the benefits of adhering to the clear zone concept seem overblown. In fact, larger tree canopies are associated with improved road safety outcomes whether we are talking about total crashes or focusing on just injury and fatal crashes. The prevalence of street trees in terms of the number per mile did not play a significant role in segment-related crash outcomes. In other words, more street trees per mile does not seem to make street segments less safe; conversely, fewer trees does not make street segments safer. However, when also considering intersection crashes, the number of street trees per mile associates with improved safety across all severity levels in wealthier neighborhoods, but worse safety in low-income neighborhoods. Although we can speculate as to what might be causing this inconsistency, it is an equity issue that deserves future research.

With regards to re-evaluating how we value transportation, what can we glean from results such as these? First, we should not take for granted the efficacy of design practices conjured in vastly different contexts. For instance, the GM Proving Grounds intended to simulate limited-access highway conditions outside of built-up human activity. When high-speed highway crashes take place in this context, limiting fixed-object hazards in the roadside makes sense. If the empirical results hold true in the real world, then it would be logical to establish appropriate design criteria. However, imparting the wisdom of highways onto urban streets in built-up areas surrounded by human activity may not have the desired effect. In other words, it does not make much sense to focus our efforts on trying to reduce the consequences of high-speed crashes that are not desirable in the context of urban areas in the first place. This is particularly problematic without sufficient empirical data for such recommendations to have been made in the first place, and in the case of urban clear zones, there was not. This study begins to fill this gap, but there needs to be much more work to truly gain clarity on the clear zone concept. It is also interesting to note the evidence that rural areas may not be seeing the expected safety gains either. Lee and Mannering, for example, studied run-off-the-road crashes in Washington State and found wider lanes and shoulders associated with more crashes and fixed-object hazards with fewer crashes (Lee & Mannering, 1999). Ivan et al. found evidence of crash migration with reductions in fixed-object crashes being offset by more total crashes and multiple-vehicle crashes in rural Connecticut (Ivan, Raghubhushan, Pasupathy, & Ossenbruggen, 1999). A related study of New Hampshire expected worse safety outcomes with more trees in the clear zone, but found the opposite (Ossenbruggen, Pendharkar, & Ivan, 2001).

The second inference we can take from our results relates to the pervasive underestimation by engineers of how design differences might influence human behavior changes. In the popular-press book, *Traffic*, Tom Vanderbilt highlights the 1908 story of Colonel Willoughby Verner, who had written a letter to his local newspaper about how he recently cutting back his hedges from the intersection near his home (Vanderbilt, 2008). At the request of the local motor union, Verner trimmed his hedges back nearly 30 yards and to a height of 4 feet. Much to his surprise, Verner found that vehicle speeds dramatically increased after the hedges had been cut back. When Verner discussed the issue with the police, they told him that people were now driving faster because they could see around the corner and felt safe doing so at higher speeds. In response, Verner allowed the hedges to fill back in, and cars began to slow down (Vanderbilt, 2008). Figure 6.1 is an excerpt from an FHWA document titled, Vegetation Control for Safety, that depicts “satisfactory” and “hazardous” conditions at an intersection (Eck & McGee, 2008). If traffic speeds remain constant, then it stands to reason that the condition deemed satisfactory is safer; however, if fewer trees result in different driver behaviors and higher vehicle speeds, then the question of safety is much more complicated.

This concept of risk compensation is at the heart of the argument for why street trees might lead to better safety outcomes (Adams, 1995; Vanderbilt, 2008). The idea is that making a street feel narrower – and perhaps even feel more dangerous as well – could entice people to behave differently and perhaps more safely. Related to this theory, Dumbaugh and Gattis discuss the concept of a self-enforcing or self-explaining street that, in essence, provides the driver guidance on an appropriate driving speed (Dumbaugh & Gattis, 2005). The goal of a self-enforcing street is to use design elements rather than signage or police enforcement to manage vehicle speeds. In the case of street trees in clear zones, the increased visual complexity and more pronounced street edge have been shown to be associated with reduced driving speeds (Burden, 2006; Godley, Fildes, Triggs, & Brown, 1999; Naderi, Kweon, & Maghelal, 2008). Speed reduction can, in turn, impact road safety outcomes, particularly with respect to fatal and severe injury crashes.

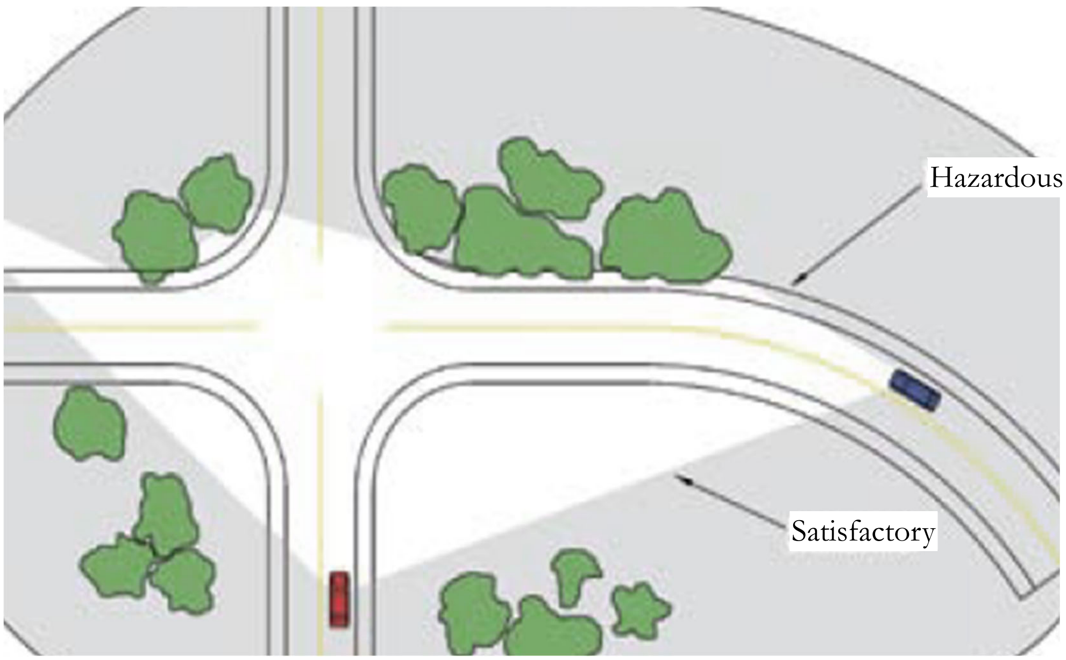

Figure 6.1 "Satisfactory" and "Hazardous" Intersection Treatments (Eck and McGee 2008)

How does all of this impact the business and management policies of, for instance, a municipality or transportation agency? Planting an urban street tree, including three years of maintenance, costs between $300 and $750, but the economic return of a single street tree seems to far exceed the initial costs (Burden, 2006). By estimating the value of air conditioning savings, erosion control, wildlife habitat, and air pollution reduction over the life of an average urban tree, the American Forestry Institute estimated this benefit as just over $100,000 in today's dollars (Moll and Young, 1992). This estimate does not account for the research, suggesting that street trees add value to adjacent homes, businesses, and the tax base (which may explain the confounding relationship of household income on some of our results) (Das, 1979; Burden, 2006) nor does it account for the economic and human health benefits related to fewer and less severe crashes, as suggested by our results.

Despite the economic and environmental advantages of street trees and the growing body of literature highlighting potential road safety benefits, tree removal policies – long ago reserved for highways and rural locations – continue to be commonplace in many urban settings (West, 2000). For instance, the Kentucky Transportation Cabinet recently removed 17 newly planted trees along an urban street in Louisville, and even charged the city $17,000 for the expense, saying these trees should not have been planted in the clear zone in the first place (Bruggers, 2014). The district engineer said, "We are not anti-tree at the Transportation Cabinet; we are pro-safety," and went on to cite the need to preserve the clear zone (Bruggers 2014). While more research is needed, there is already enough evidence to say that such statements should no longer be made without qualification. Beyond their economic and environmental benefits, street trees have long been a staple of good urban design and shaping more livable spaces. They may also support slower speeds, greater road user awareness, and in turn, improved road safety outcomes.

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PART 2: THE USE OF AERIAL LIDAR IN MEASURING STREETSCAPE AND STREET TREES[4]

8. INTRODUCTION

Light Detection and Ranging (LiDAR) is a highly sophisticated Geographic Information Systems (GIS) and remote sensing technology. Over the last couple decades, GIS and related technologies have played significant and often behind-the-scene roles in both basic transportation spatial database management uses and comprehensive transportation planning. LiDAR is now beginning to be used commonly for transportation purposes, such as to guide autonomous cars. For example, researchers in LiDAR sensor technology are working toward better object sensing to make the autonomous vehicles' object detection capabilities more reliable (Funke, Brown, Erlien, & Gerdes, 2017). However, LiDAR has not yet been adapted for much in terms of more fundamental transportation research.

The United States Geological Survey (USGS), with support of other agencies, is investing tens of millions of dollars annually to acquire LiDAR throughout the United States as part of its National Elevation Enhancement Program (NEEP) or 3D Elevation program (3DEP), which launched in 2011. The USGS lists flood risk management as the most important beneficiary of the NEEP program. However, infrastructure/construction management, natural resource conservation, agriculture and precision farming, water supply/quality, forest resource and wildfire mitigation, and aviation navigation/safety are all listed by USGS as business uses to benefit from the NEEP program (Snyder, 2012).

Since NEEP LiDAR is publicly available and covering more area within the U.S. each year, the goal of this section is to determine if LiDAR data collected at NEEP standards can play a pivotal role in streetscape assessment. More specifically, we will attempt to assess the 3D measurements of objects within streetscape boundaries and compare the results against commonly derived 2D polygons of objects. Improved measurements of streetscapes will, hopefully, lead to breakthroughs in what could be described as diverging research results with respect to streetscape elements and various transportation-related outcomes. For instance, with street trees, the research has long been conflicted over their influence on road safety outcomes (Eric Dumbaugh, 2005a; Wolf & Bratton, 2006; Zeigler, 1986). Some studies suggest that street trees are associated with better safety outcomes (Marshall, Coppola, & Golombek, 2018), while other studies find them to be hazardous (Turner & Mansfield, 1990; Zeigler, 1986). One reason for inconsistent findings may be that few existing studies adequately measure streetscapes. For streetscape mapping, we must decipher between objective versus subjective measuring methods. The older studies focus on crude, and sometimes subjective, measures such as manual tree counts. This section attempts to introduce a much more objective measuring method by incorporating aerial LiDAR, a technology proven for its high accuracy measuring techniques.

Airborne LiDAR – with its large swath survey grade surface model compilation capability and multi-point return characteristic – has evolved into the preferred method for tree canopy collection (Lesky, Cohen, Parker, & Harding, 2002). A fundamental difference between an assessment that utilizes LiDAR canopy data versus specific tree count, or two-dimensional polygons derived from remote sensing imagery, is the spatial characteristics of these methods. Tree counts display an accurate accounting of the specific number of street trees. Polygons derived from common imagery sensors like Quickbird display canopy coverage area only. When assessing streetscapes, both tree counts and 2D canopy polygons displayed individual tree quantities and canopy areas, respectively. However, both methods have severe

[4] This portion of the report has been peer-reviewed and published: Golombek, Y, and Marshall, W. Use of Aerial Lidar in Measuring Streetscape and Street Trees. *Transportation Research Record*, No. 2673: 125-135, 2019 (doi.org/10.1177/0361198119837194).

limitations with respect to incorporating tree characteristics themselves. In addition to trees, other stationary objects within a streetscape are also important to assess, such as signs, light poles, and buildings, to name a few.

This section will present a comprehensive methodology for measuring 3D characteristics of trees within a streetscape as well as other large 3D objects, such as powerlines, light poles, and signs. Additionally, this section will measure and statistically assess the 3D street-tree delineations against 2D-derived tree polygons from LiDAR to show if and how 3D measuring of streetscape objects differs from conventional 2D assessments.

The data used for this assessment are USGS Quality Level 2 (QL2) data, scheduled to be produced for the conterminous United States (CONUS) and Hawaii within the next eight years (Hans Karl Heidemann, 2018). QL 2 LiDAR data have a nominal point spacing of around 0.5 meters, or a point density of around 2 points per square meter. If our assessment can be adequately performed with QL2 data, then it can become common practice and widely applied in many municipalities (where QL2 or better data already exist) and eventually in most municipalities across the United States for assisting to assess 3D characteristics of features within streetscapes.

9. LITERATURE REVIEW

Over the past two decades, the improvement of quality and accuracy of remote sensing technologies has impacted transportation research.

In the early 2000s, the Transportation Research Board held three annual seminars as part of the National Consortium on Remote Sensing in Transportation (NCRST) (Remote Sensing for Transportation Products and Results: Foundations for the Future, 2001). The conferences were a response to increased demands to assess new methods and technologies to enhance the planning, designing, managing, operating, and maintaining of all modes of transportation, noting that aerial and satellite remote sensing were experiencing rapid development at that time. Aerial Lidar was in its infancy and used in conference case studies for airport and runway glide-slope measuring for obstruction mapping. Other LiDAR case studies were related to traditional LiDAR uses, such as alignment surveys, roadway flood risk, and general terrain mapping. In total, 37 projects were displayed at the 2001 seminar alone. Yet, none of them were focused on urban object mapping applications, likely because the technology at that time was primitive compared with today's remote sensing technology. The seminars seemed to focus on various forms of feature extraction from GPS verified ortho-imagery, and also included topographical studies from very low-resolution satellites, at least by today's standards.

Relating to street mapping, a recent study looked at utilizing high resolution satellite and aerial images. This study used an algorithmic, intensity, and image classification methodology to pick out a variety of road segments in an automated way. The results were improvements over older imagery-based extraction studies, but still not overly impressive (extraction accuracy ranged from 86% for higher class roads to 67.3% for lower class roads) (Luo et al., 2018). With the streets themselves being among the most contrasting and identifiable objects in a streetscape, these results suggest that automated imagery extraction practices would not likely yield accurate results for individual streetscape mapping. When LiDAR is consolidated with imagery extraction approaches, street feature extractions are significantly more accurate (Shyue, Huang, Lee, & Kao, 2012).

A study by Yin (Yin, 2017) evaluates streetscape measures related to walkability research conducted by Ewing and Handy (Ewing & Handy, 2009) and Purciel and Marrone (Purciel, M., & Marrone, 2006). These authors defined the streetscape features qualitatively and developed a comprehensive manual to guide field observation for quantitative measures of these features. These measures, however, were based on observational tools that require extensive manual labor and estimated measures through sometimes subjective observations, which can be inconsistent across the raters (Yin, 2017). In Yin's study, GIS and remotely sensed imagery were utilized to extract buildings and trees, among other features. Height attributes from the assessor database gave buildings their heights, and trees were grouped into small, medium, and large categories. Recent studies found that objective measures of the built environment had stronger associations with walking than subjective measures, and suggested future studies to include objective measures (Lin & Moudon, 2010; Yin, 2014). Yin's study builds on these previous works by using remote sensing and 3D GIS to objectively measure street level urban design qualities and test their correlation with observed data. The statistical results concluded that 3D GIS helped generate objective measures on view-related variables. Additionally, if Yin's study utilized the highly accurate measuring capabilities of LiDAR, the results would likely yield even more objective results.

A comprehensive 2014 New York City study with a significant LiDAR/GIS focus incorporated nearly 240,000 crashes over nearly 75,000 road segments to study street-side characteristics on crashes. This study incorporated many variables, including trees, buildings, cross-section widths, and street types, to name a few (Harvey & Aultman-Hall, 2015). This study derived LiDAR-based tree canopies as part of the study. Of all features/variables studied, street enclosure due to tree canopy, by far, had the largest association with crash outcomes. However, this study appears to analyze 2D tree polygon coverage area only within a streetscape, neglecting 3D tree features. For example, if two streetscapes had 15% total tree coverage, one could have significantly more tree density/biomass, because the 3D characteristics are not taken into account. These types of characteristics may be critical for understanding the impact of urban streetscapes on transportation-related outcomes.

Recently, a graph-cut segmentation method was used to extract street poles from mobile LiDAR (Zheng, Wang, & Xu, 2017). The authors' proposed method extracted features with an overall detection probability of greater than 90%. Mobile LiDAR is far more dense and accurate than traditional aerial LiDAR. Unfortunately, large-scale mobile LiDAR collection and processing efforts are costly. Due to the current early stages of the technology, automated extraction efforts are not common, and classification of features is very time consuming. A purpose of this study is to propose streetscape measuring techniques with data collected for the U.S. national LiDAR database, and there are no plans in sight to incorporate mobile LiDAR into the USGS national database.

10. DATA & METHODS

10.1 Overview

In this section, we investigate new 3D methods for measuring streetscape features given common data available from the USGS national dataset. The Harvey and Altman-Hall study mentioned above analyzes buildings and trees against crash data, while a different study by these authors focuses on a building location and characteristics as a prime feature for assessing streetscapes. (Harvey, Aultman-Hall, Troy, & Hurley, 2017). Though more focused on subjective methods of measuring streetscapes for walkability, Ewing and Clemente include building characteristics and landscaping features and also include streetscape objects such as landmarks and signage (Reid & Clemente, 2013).

Buildings and trees are features commonly extracted by automated applications in LiDAR software. Other streetscape features, such as signs, landmarks, power poles, and overhanging lights (to name a few), would initially have an automated LiDAR classification of "Unclassified" or "Other" and require manual classification. Studies linking LiDAR building classifications with actual building footprints show that the LiDAR processing community has made significant inroads with producing highly accurate building footprints from LiDAR (Saraf et al., 2018; Wang, Zeng, & Lehrbass, 2012).

The same cannot be said about urban trees. Studies comparing actual tree biomass to LiDAR results have not been nearly as successful as those for buildings (Gu & Townsend, 2017; Plowright, Coops, Eskelson, Sheppard, & Aven, 2016). Also, LiDAR tree characteristics are geared toward crude mass and density figures as opposed to how trees are measured and represent themselves within streetscapes. Therefore, this methodology will focus on new methods to measure trees at different height intervals within streetscapes.

The specific unit of analysis for this study is street corridor sections, and we compare voxel data of trees to 2D-derived LiDAR tree data within street corridors (or streetscapes). In geospatial terms, a voxel is a 3D pixel and will be discussed in depth later in the Methods section of this section. To establish our study, three critical pieces of information are required: i) LiDAR derived tree canopy data, ii) street data for establishing streetscapes, and iii) tree-point data containing attributes about the trees ultimately linked to the tree polygon data.

10.2 Tree Data – LiDAR

LiDAR collected for the entire Denver area during leaf-off conditions is publicly available by USGS. These data have a nominal point spacing of approximately 0.7 points per meter, similar to the QL2 data the USGS requires. As a form of aerial surveying that outputs x,y,z survey points in the form of a very dense standard (.las) point cloud file, LiDAR does not contain the geometric distortions present with other aerial remote sensing platforms, which is why LiDAR is now considered a preferred method for such measurements.

The area of interest (AOI) covers approximately 21 square miles (nearly 15% of Denver's boundary) of a fairly uniform part of Denver and contains 20 LAS LiDAR point-cloud files. A software called MARS (produced by Merrick & Company), which is discussed in more detail below, was used to filter out the tree data and to create tree polygons of canopy areas. A total of 142,300 tree polygons were derived from this 21-square-mile AOI. The 2D and 3D tree modeling process is described in more detail in Figure 10.1.

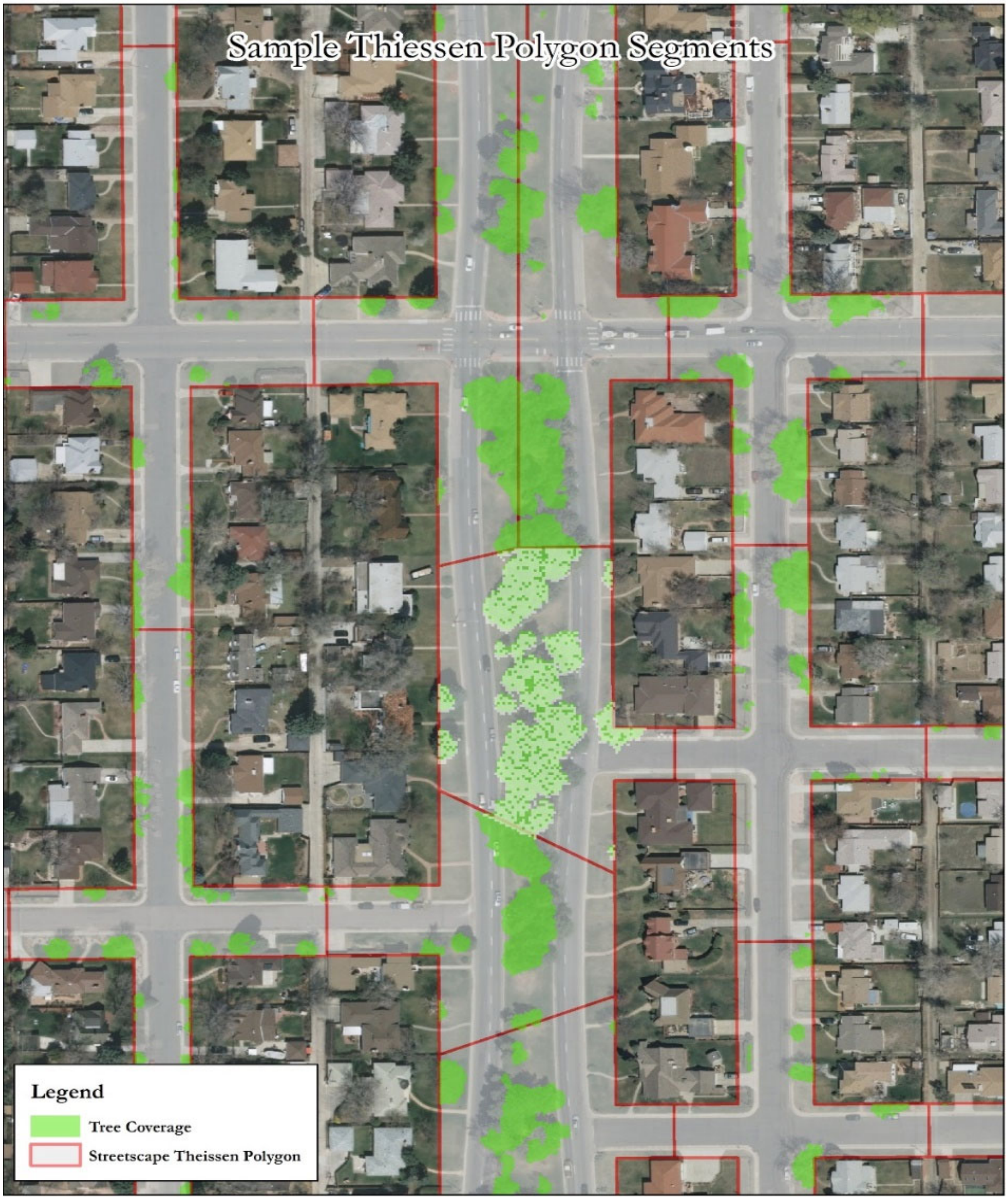

Figure 10.1 Example of street segment units divided into Thiessen Polygons with tree coverage; the center polygon contains a 3D aggregated example of the height intervals

10.3 Tree Data – Tree Points

Denver's Department of Parks and Recreation maintains GPS point data from various parts of the city. Fortunately, Denver maintains a complete tree inventory covering a significant part of the AOI specified above. A shapefile of the data was downloaded, and the AOI was clipped from the data. A total of 48,598 roadside trees were present in the AOI. The tree point data will not be used in the analysis. However, the data are important because they denote tree species. The LiDAR data were collected during leaf-off, which is common for USGS 3DEP since ground topography is a priority of the 3DEP program. For mapping forest structure, LiDAR data are optimally collected under leaf-on conditions, while leaf-off LiDAR are preferred for ground detection needed to map elevation (Anderson, Thompson, & Austin, 2005). Therefore, the tree point layer can assist with segregating deciduous and non-deciduous trees, since the collection period was during leaf-off.

10.4 Street Network Data / Street Segments

The unit of measure for our study is the street segment. We first divide the AOI into Thiessen proximal polygons (or Voronoi polygons, as mathematicians call them). Thiessen polygon datasets are mutually exclusive, non-overlapping, and cover the entire AOI. Thiessen polygons are used in this model because they divide the polygons (streetscapes in this case) in a clean and uniform manner, and they can be created with a GIS application around a designated focal point set. The focal points for our project are the intersections. In urban streetscapes, the intersections are areas of high activity; therefore, we made the intersections the centroids. The Thiessen/Voronoi method gives weights to high event areas and is a popular model and spatial method for focusing on focal event points (Gold, 1991).

Additionally, the street right-of-way (ROW) data extend beyond the boundary of each street curb. Approximately 10 to 20 feet of LiDAR tree coverage data are clipped to the ROW in order to perform analysis on the features that interact with not just the roadways, but the peripheral views within a streetscape.

10.5 3D Characteristics of Tree Canopies

When considering grid spacing for voxels, we must consider an optimal vertical and horizontal voxel size. USGS stresses the importance of regularity of point patterns for horizontal spacing throughout a dataset, and requires a spatial distribution of at least a point per grid cell (Hans Karl Heidemann, 2018). Since the statistics of the LiDAR used in this study have an average point spacing of around 2 feet, we adhere to USGS standards and set the horizontal voxel spacing to 3 feet in order to assure the vast majority of the AOI will contain at least a LiDAR point per grid space.

When setting the vertical size of the voxel, other factors must be considered, particularly the concept of occlusion, or occluded data. Once all pulses intersecting the voxel grid were traversed, a classification grid is established. The voxel classification discriminates between voxels observed with (filled) and without (empty) a laser return inside the voxel. Voxels that were completely hidden from the laser instrument are considered occluded. Occluded voxels are those theoretically traversed by the pulses, meaning the pulses would have reached the voxel, but all energy was already intercepted due to earlier interactions of the laser pulses with canopy material (Kükenbrink, Schneider, Leiterer, Schaepman, & Morsdorf, 2017).

An in-depth study by Kükenbrink et al. is one of the few studies that address occluded voxels to attempt to minimize their presence. The study notes that occlusion under leaf-off conditions accounts for only 1.5% of total canopy volume, as opposed to 25% for leaf on or non-deciduous conditions. Fortunately, the data in this study, along with most required USGS-sponsored LiDAR datasets, require leaf-off conditions to maximize ground point coverage. However, this factor will force us to consider separating deciduous and non-deciduous trees, such as pine trees, that do not shed their leaves.

Kükenbrink et al.'s study notes that the larger the voxel size, the lower the percentage of occluded canopy and the higher the percentage of observed canopy. It is important to keep this in mind while considering the focus of this study, which is the ability to measure features in streetscapes in three dimensions. The 1.5% minimal leaf-off occlusion represents a pixel 5 meters in height. Yet, this study is attempting to sectionalize a streetscape in smaller intervals in order to ultimately try to analyze how streetscape features affect fundamental transportation outcomes such as road safety. Therefore, we compromise with a 1.5 meter (5-ft tall) voxel. This allows the streetscape to be divided into 5-ft vertical intervals, yet the occluded data are still relatively low at less than 10% for leaf-off conditions per the statistics present in Kükenbrink et al.'s study.

In addition to Kükenbrink et al.'s study, a voxel study in southern Sweden, which correlated tree characteristics and crown base height based off actual field measurements, utilized similar LiDAR criteria to the QL2 data and returned an R2=0.84 (Holmgren, Persson, & Söderman, 2008). A voxel-based method in eastern Texas did the same and concluded that a LiDAR height-bins (i.e., voxels) approach has high potential for becoming the standardized method for processing and exchanging forestry LiDAR data (Popescu & Zhao, 2008).

10.6 Quantitative Tree Canopy Zones within Street Segments

Since state plane coordinates, a feet-unit-based system, are used as a common system to link the different data features in this study, a voxel of 3 feet in width and 5 feet in height is used. The maximum height of trees resulting from the LiDAR in the AOI is 90 feet; therefore, 18 zones are created, with each zone being 5 feet in width. Unlike forested areas where LiDAR points end at ground or natural features, there is a high tendency for point interference at the lowest layer of these zones due to reflectance of cars and other objects beneath the tree crown. To eliminate this point interference below urban tree crowns, we exclude the first zone, as is common for urban tree characteristic studies from airborne LiDAR, since the interference may have a tendency to distort the data classification (Hollaus et al., 2010; Koma, Koenig, & Höfle, 2016). Therefore, our analysis is performed on 17 zones, the first zone being 5 to 10 feet in height and the last zone being 85 to 90 feet in height.

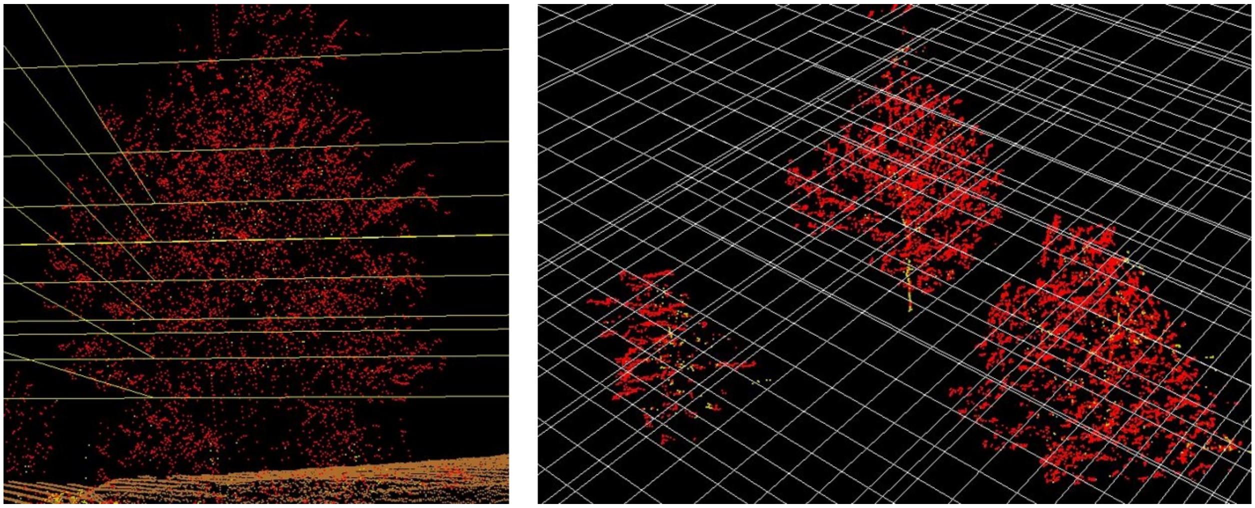

Figure 10.2 Left: example of height interval zones across a LiDAR point cloud; Right: example of 3D voxels covering a group of trees

In our AOI, the street segments are calculated into 2,119 Theissen polygons that also consist of the Denver tree point data mentioned above. Since the vast majority of trees in the AOI are deciduous, and calculating density features on deciduous and non-deciduous trees during leaf-off collection yields different results, we use Denver's tree point dataset to filter out polygons with non-deciduous trees. The result is 1,445 Theissen polygon street segments in east Denver, which will be the basis of this analysis.

As mentioned above, a software called MARS (produced by Merrick & Company) was used to filter out the tree data and to create tree polygons of canopy areas. Creating 2D LiDAR tree canopy polygons is a common LiDAR software procedure where the software will detect light energy characteristics of multi-point return vegetation data within the point cloud, then smooth and cluster the data to create polygon features out of trees. The same MARS software is used to derive the voxel zones as well, where point cloud data are extracted from each specified zone. The voxels are exported to ENVI-based .dat, which are one of the few volumetric pixel data sets available. The resulting export is 1,445 .dat files, where each .dat file has 17 bands, and each band represents a single elevation zone within each street segment.

GIS applications and processing take the raster-based .dat files and convert them from raster into vector data, where canopy data for within each zone are polygons within the street segment polygons. The end result is a street segment polygon layer with 1,445 records, where each record represents a street segment. This layer also has two fields for each zone. The first being the area (in square feet) of total canopy coverage in a street segment, and the second being the percentage of area in each zone per street segment. Since a major purpose of this study is to evaluate 3D streetszone measuring techniques against similar 2D results and to show their differences, the 2D-derived LiDar data are appended to this layer, along with aggregate data from all zones combined.

10.7 Statistical Methodology

We are trying to answer the following question: Is there significant coverage variation in roadside trees at different height intervals, and does the holistic measuring of trees at different height intervals have any correlation with the traditionally derived 2D polygons from LiDAR? If we find significant variation, then it is imperative that 3D characteristics be taken into account when assessing roadside tree characteristics. If not, then a 2D delineation of roadside trees should be sufficient.

In this case, the dependent variable is the 2D delineation of the LiDAR street tree data derived in this study, and the explanatory variables are the 3D quantities of each zone. We assign the 2D polygon delineation as the dependent variable, since it is a single variable that represents all 2D polygon classifications. Since the 3D voxel derivation has different data at each height interval, and since we are interested in correlations between these intervals and the 2D LiDAR derived polygons, we set the 3D height zones as the explanatory variables. We note that the dependent variable is not normally distributed. However, we are only looking for a descriptive summary of relationships between each tree zone and their corresponding 2D canopy coverage. An ordinary least squares (OLS) regression model can be used to describe the relationships between two or more variables in a sample without making any assumptions when the dependent variable is continuous, and that the relationships between these variables are linear. As a result, regression models can be used in a descriptive manner to summarize the relationships between the variables in a sample (Allen, 1997). Therefore, we will run an OLS regression test on the tabular data for 2D vs. 3D data on each road segment.

$$y_n = \sum_{i-0}^{k} \beta_i \, x_{ni} + \varepsilon_i$$

y_n= Percentage of 2D canopy coverage per street segment
x_{ni} = The individual coverage variables for each height zone
β_i = Estimated vector of coefficients representing effects of the covariates
ε_i = Stochastic component representing random error used to account for overdispersion

The OLS is used to show how the various height zones modeled compare with the dependent variable, which is the 2D single layer derived LiDAR canopy. To assess whether the means of the various zones contains statistical significance with each other, we use an analysis of variance (ANOVA), which works optimally with normally distributed data. When data are not normally distributed, non-parametric tests, specifically the Kruskal-Wallis test (commonly known as the non-parametric version of the one-way ANOVA), is often used instead of ANOVA. Though for this dataset, there are a couple of problems with the Kruskal-Wallis test. First, like other non-parimetric tests, the Kruskal-Wallis is a statistics rank test, and this dataset is not one that involves ranking. Second, the Kruskal-Wallis does not work well with large datasets (Fan & Zhang, 2012; Minitab, 2018).

Studies show that non-normal data are appropriate for one-way ANOVA or other parametric tests. Fortunately, an ANOVA is not very sensitive to moderate deviations from normality; simulation studies, using a variety of non-normal distributions, have shown that the false positive rate is not affected very much by this violation of the assumption. Also, ANOVA tests are valid when the variables being tested have similar patterns of distributions and variances (Glass, Peckham, & Sanders, 1972; Lisa M. Lix, 1996), as the 2D and 3D canopy data clearly displays.

Sum of Squares Formula

$$SS_{total} = \sum_{j=1}^{p} \sum_{i=1}^{n_j} (y_{ij} - \bar{y}_i)^2$$

$$SS_{between} = \sum_{j=1}^{p} n_j (\bar{y}_i - \bar{y}_{...})^2$$

$$SS_{within} = \sum_{j=1}^{p} \sum_{i=1}^{n_j} (y_{ij} - \bar{y}_{...})^2$$

Mean Squares Formula

$$MS_{between} = \frac{SS_{between}}{df_{between}}$$

$$MS_{within} = \frac{SS_{within}}{df_{within}}$$

F Squares Formula

$$F = \frac{MS_{between}}{MS_{within}}$$

$\bar{y}_{i.}$ mean of the observations at each elevation zone
$\bar{y}_{..}$ mean of all observations
y_{ij} value of each elevation zone (i) as a factor of (j) zones.

When performing an ANOVA on the dataset, we will evaluate the entire dataset and individual sections in order to see if certain patterns about relationships of the means develop between the different zones. Since this study looks to either justify or dismiss the need for 3D measuring of trees vs. 2D measurements, exploring the differences or similarities of means assists us in this determination.

11. RESULTS / DISCUSSION

11.1 Statistical Results

At the QL2 level of point cloud density, only buildings and trees can be derived in an automated process. Other features in a streetscape, such as signs, light-poles, power-poles, and overhead streetlights, require in-depth manual filtering of the data, assisted with high resolution imagery or processed paired with a Google StreetView type application. Per Figure 11.1, only a handful of QL2 LiDAR points hit street lamps and traffic lights in a sample Denver intersection.

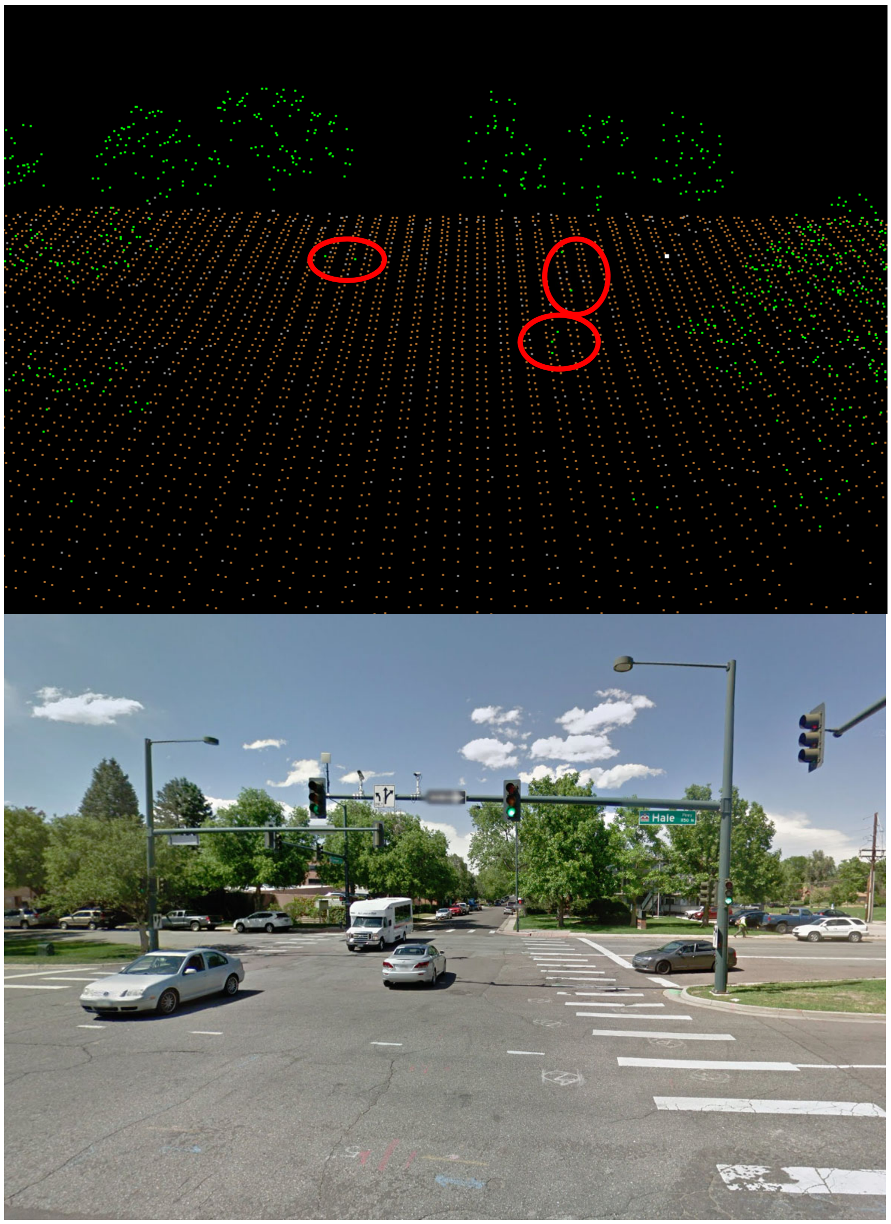

Figure 11.1 QL2 Data of Street Intersection; Street Light and Traffic Light Features are Circled in the Top LiDAR Point-Cloud

These features yielded zero to a few sporadic points per feature and could not be deciphered by QL2 density LiDAR by itself. A 2011 study by Shiahn-Wern et al. attempts to build on developed methods and hybrid approaches to assist with feature extraction. It also notes the intensive research that has been undertaken on classification of natural and man-made features from aerial LiDAR in urban environments; yet, the study is only limited to trees, buildings, grass, and roads (Shyue et al., 2012). Therefore, we accept that smaller man-made objects within a streetscape cannot be determined in similar ways to trees and buildings via a simple, automated process when using QL2 LiDAR data.

Table 11.1 OLS Regression Results

Variable	Coefficient [a]	StdError	t-Statistic	Probability [b]
Intercept	0.01	0.00	8.17	0.00*
3D Poly Aggregate	1.82	0.03	58.44	0.00*
Zone 2 (5ft to 10ft)	-0.36	0.19	-1.92	0.06
Zone 3 (10ft to 15ft)	-0.14	0.15	-0.91	0.36
Zone 4 (15ft to 20ft)	-0.50	0.14	-3.47	0.00*
Zone 5 (20ft to 25ft)	-0.52	0.14	-3.76	0.00*
Zone 6 (25ft to 30ft)	-0.18	0.15	-1.25	0.21
Zone 7 (30ft to 35ft)	-0.61	0.14	-4.20	0.00*
Zone 8 (35ft to 40ft)	-0.44	0.15	-2.87	0.01*
Zone 9 (40ft to 45ft)	0.07	0.16	0.43	0.67
Zone 10 (45ft to 50ft)	-0.66	0.17	-3.96	0.0*
Zone 11 (50ft to 55ft)	0.07	0.18	0.40	0.69
Zone 12 (55ft to 60ft)	-0.42	0.18	-2.27	0.02*
Zone 13 (60ft to 65ft)	-0.36	0.23	-1.56	0.12
Zone 14 (65ft to 70ft)	-0.29	0.31	-0.91	0.36
Zone 15 (70ft to 75ft)	0.15	0.48	0.31	0.75
Zone 16 (75ft to 80ft)	-0.54	1.00	-0.54	0.59
Zone 17 (80ft to 85ft)	-1.25	1.72	-0.73	0.47
Zone 18 (85ft to 90ft)	0.73	4.43	0.16	0.87
Number of Observations	1445			
R^2	0.97			

Table 11.1 notes the descriptive summary within the zones, with the 2D LiDAR derived polygons set as the dependent variable, per the OLS linear regression test. As expected, we see the strongest relationship with the aggregated 3D-derived polygons with the 2D canopy/dependent variable. Per Figure 10.1, the 3D aggregated canopy layer is modeled directly off the 2D-derived layer. The only difference being that some holes will exist in the 3D-aggregated layer where LiDAR hits penetrated straight to the ground. Empty spaces in these features are a factor of the tree density since the voxel grid illustrates the density of the data being collected. In simpler terms, when one can see sunlight through a tree canopy, these are often areas where a LiDAR point would penetrate straight to the ground without recording a hit on the tree.

From these results, we find that the coefficients and t-stats/p-values are quite sporadic throughout the different zones modeled, and even more so in the upper layers. The weak and sporadic coefficients compared with the aggregated 3D model indicate weak relationships between the individual zones and the dependent variable. Even more noteworthy is there seems to be no pattern of which zones have stronger or weaker coefficients, and also those data seem sporadic and unorganized. We infer from these sporadic patterns that measuring streetscape features in 3D are significantly different than the commonly used 2D-derived LiDAR tree polygons, and that the 2D polygons do not provide an objective accountability of what the streetscape actually looks like or how it is quantified. Next, we look at the results of the ANOVA single factor test on different groups of data where $\alpha = 0.05$.

Table 11.2 ANOVA Results for All Zones 2D and Aggregated 3D Polys and 3 Height-Zones with Closest Characteristics

ANOVA: Single Factor

Groups	*Average*	*Variance*
2D Poly Area	18.44%	0.0132
3D Poly Aggregate	13.15%	0.0072
Zone 2 (5ft to 10ft)	0.56%	0.0000
Zone 3 (10ft to 15ft)	1.39%	0.0001
Zone 4 (15ft to 20ft)	1.95%	0.0001
Zone 5 (20ft to 25ft)	2.19%	0.0002
Zone 6 (25ft to 30ft)	2.17%	0.0002
Zone 7 (30ft to 35ft)	2.02%	0.0002
Zone 8 (35ft to 40ft)	1.87%	0.0002
Zone 9 (40ft to 45ft)	1.69%	0.0002
Zone 10 (45ft to 50ft)	1.46%	0.0002
Zone 11 (50ft to 55ft)	1.20%	0.0002
Zone 12 (55ft to 60ft)	0.91%	0.0001
Zone 13 (60ft to 65ft)	0.60%	0.0001
Zone 14 (65ft to 70ft)	0.31%	0.0000
Zone 15 (70ft to 75ft)	0.13%	0.0000
Zone 16 (75ft to 80ft)	0.04%	0.0000
Zone 17 (80ft to 85ft)	0.01%	0.0000
Zone 18 (85ft to 90ft)	0.00%	0.0000

Count: 1445

	Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
All Zones	Between Groups	59.52	18	3.31	2801.81	0	1.60
	Within Groups	32.38	27436	0.00			
	Total	91.89	27454				
2D Poly Area and 3D Poly Aggregate	Between Groups	2.02	1	2.02	197.63	0.00	3.84
	Within Groups	29.54	2888	0.01			
	Total	31.56	2889				
Height Zones 5, 6 & 7	Between Groups	0.00	2	0.0012	5.56	0.00	3.00
	Within Groups	0.90	4332	0.0002			
	Total	0.91	4334				

In Table 11.2, we ran the ANOVA on three different variations of the data. One variation was all the data grouped together, one was only assessing the 2D polygon areas with the 3D aggregated polygons, and the third looked at three zones (specifically zones 5, 6, and 7). The 'Average' field statistic in Table 11.2 notes the average percentage of canopy coverage for that zone throughout the 1,445 Thiessen polygons in the sample dataset. The result of running the data on all the zones and only the 2D polygons and 3D aggregate polygons resulted in very high F values, leading to p-values of at or very near zero. These test scores suggest there is extreme variation between the means of the different zones and variation within the zones themselves.

Since Zones 5, 6, and 7 were closest in range of all zones, we ran the ANOVA on only those zones to see if we could find any patterns or similar means. Though the F value in this group was reduced significantly from the other examples, it still resulted in a p-value near zero. This indicates that even zones with the closest average coverage values still have significant differences of means.

What we learn from these two statistical tests is that when assessing roadside trees within a streetscape, the 3D measurements detail different measures from the commonly used 2D GIS polygons, both of which originate from the same LiDAR derived tree canopies. We see that predictions cannot be made with basic statistics from one height zone to the next, giving merit to the need to assess the complete picture rather than 2D canopy data when trying to assess the role trees play in transportation-related research outcomes.

11.2 Occlusion and Deciduous versus Non-Deciduous Trees

This statistical assessment considered the differences of occlusion that occur between deciduous and non-deciduous trees, noting that LiDAR data are rarely lost in deciduous trees when collected during leaf-off conditions. In this study's AOI, 3,250 of the roadside trees out of 48,598 total trees were non-deciduous (mainly pine species). Figure 11.2 visually compares aggregated 3D polygons layers on top of 2D canopy layers (green) of both non-deciduous and deciduous trees. Green pixels either do not contain a LiDAR pulse or contain a clear canopy opening where the pulse simply penetrates to the ground. Since non-deciduous trees have high potential for occluded LiDAR and therefore inaccurate modeling, we chose not to assess them in this study and eliminated any Thiessen polygons that included non-deciduous trees.

Figure 11.2 shows examples of leaf-off and non-deciduous pine trees of similar height. Upper height zones are pink while the lower height zones are yellow. For visual analysis, the lower yellow layers are stacked on top of the upper pink layers in the GIS. The crown-spreads are circled. Figure 11.2 notes how the thick structure of the non-deciduous pine can obstruct LiDAR from hitting the lower parts within the tree, since the lower (yellow) zones have no LiDAR returns and Google StreetView confirms dense foliage throughout. However, LiDAR penetrates most parts of the deciduous, leaf-off crowns all the way to the ground, allowing accurate 3D tree modeling. This visual appears to support Kükenbrink et al.'s study showing how non-deciduous trees obscure LiDAR below the canopy.

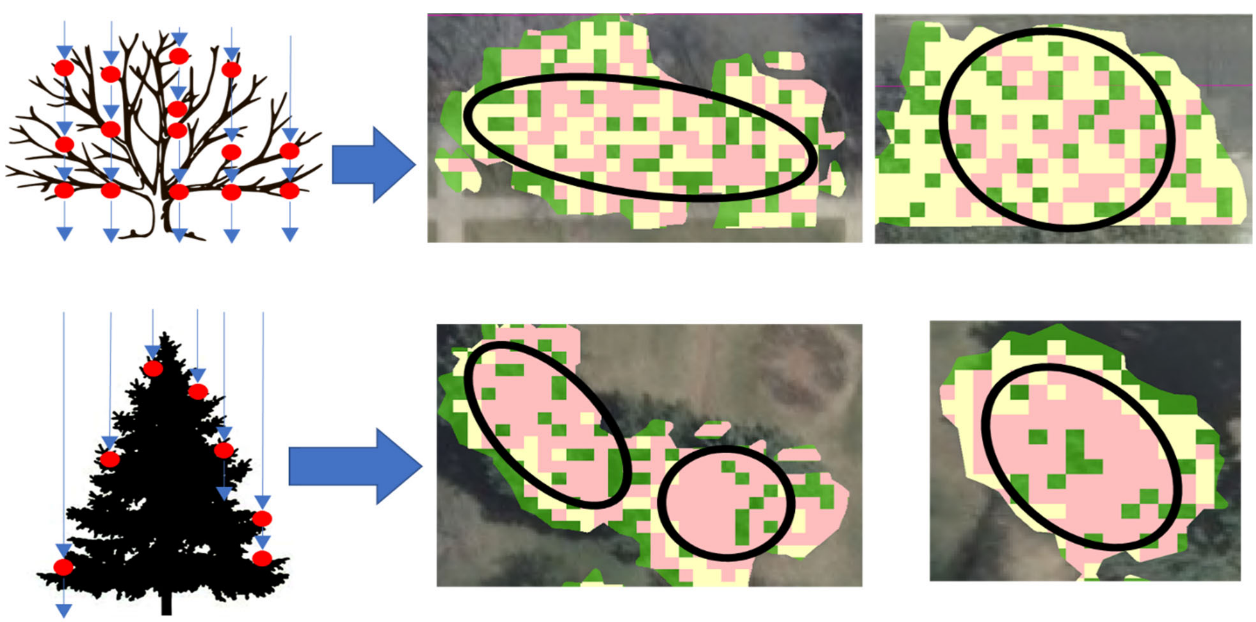

Figure 11.2 Deciduous and Non-Deciduous Coverage Example Overlaid Over 2D LiDAR Derived Polygons (Green)

12. CONCLUSIONS

These results suggest there are significant quantifying differences between traditional 2D and 3D modeling of trees in a streetscape. Since 3D measurements of trees in streetscapes are more objective than 2D-derived polygons, the 3D method should be considered in transportation streetscape-related topics, such as safety assessments and “livable” streets, or streets that seek to better integrate the needs of pedestrians and local developmental objectives into a roadway’s design (Eric Dumbaugh, 2005b). While 2D GIS has been widely used in planning, it is limited in terms of visualizing and analyzing physical objects that need to be understood in their solid forms with sensory information, such as texture, shape, and size, as well as in vertical dimensions and spatial relations, such as elevation, heights, volume, and space (Yin & Shiode, 2014).

2D LiDAR canopy polygons contain an area and max elevation height as their primary attributes. Attributes of a 3D polygon derived from voxel data contain a lot more. It can contain density information by noting quantities of voxels with LiDAR hits that overlap in a single canopy (Figure 12.1). The individual 3D polygons can also quantify areas at each elevation interval to provide analysts with canopy quantities at different heights to provide a much more objective view of how tree features are actually appearing within a streetscape.

LiDAR collection for studies like this is often cost-prohibitive. Yet, with the USGS NEEP or 3DEP program currently in progress, LiDAR data on a national level are available to a significant percentage of the United States with the goal of eventually covering the entire country over the next decade. Research shows that for leaf-off conditions, the current USGS QL2 data standard, which is the most common required collection standard, is appropriate for measuring street trees and building footprints in the streetscape but not much more. It is important to note that mainstream commercial LiDAR is less than 20 years old, and significant improvements in sensor collection capabilities are in process. With that, it may be possible that in another 10 years or so, much higher density LiDAR may be available that can pick up other streetscape objects. Also, mass-produced street LiDAR may be available if autonomous vehicles require LiDAR databases internally to back up potential sensor malfunctions while driving. Mobile Lidar is a new technology that collects extremely dense 3D streetscape data; yet, the processing and feature extraction is currently very labor intensive and time consuming.

The Harvey-Altman study mentioned above is one of the few studies that utilize LiDAR data to measure urban transportation safety at a large scale. This study focuses on “enclosure,” the collective effect of large objects surrounding a street, chiefly buildings and trees, to define the spatial extents of a streetscape and restrict long sight lines (Harvey & Aultman-Hall, 2015) and yields several results based on LiDAR-derived buildings and trees. Utilizing 2D LiDAR derived polygons (as in Harvey-Altman’s study) only explains maximum height of the canopy and total canopy area; yet, enclosure includes many other important factors, particularly the heights of the multiple canopy sections per canopy that encroach upon a street. Incorporating voxel mapping to extract 3D characteristics of trees along with the LiDAR filtering of buildings can significantly contribute to an enclosure matrix and provide new insights into the role of enclosure in transportation safety research.

Furthermore, relating to transportation research, this analysis is also significant because research is conflicted about the association between street trees and crashes. Traditional engineering and planning simply focused on tree counts and characteristics, as they would relate to direct impact should a car run off a road (Turner & Mansfield, 1990; Zeigler, 1986). Yet more recent studies indicate that an increased presence of urban trees and landscape improvement could help reduce crash counts (E. Dumbaugh, 2006; Naderi, Kweon, & Maghelal, 2008). Others acknowledge that the relationship between streetscape tree characteristics and crashes is still not well understood (Wolf & Bratton, 2006).

Figure 12.1 Streetscape Street-Tree Density

This research allows for objective measuring of trees in streetscapes and allows for analyzing large quantities of street segments in a single instance. This unique methodology and new concepts about measuring streetscape trees presented in this section will, hopefully, provide transportation research with a more definitive answer on the role that street trees play in transportation-related outcomes.

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PART 3: APPENDICES

14. TEACHING MATERIALS

This following first shows the assignment from CVEN 5633: Case Studies in Sustainable Transportation, followed by two examples of student work.

14.1 Assignment from CVEN 5633: Sustainable Transportation

14.1 1 Example of Student Output No. 1 for CVEN 5633

Case Study No. 1 – Street Trees & Safety

CVEN 5633: Case Studies in Sustainable Transportation

Due Dates

Report: March 13th by midnight

Presentation: March 14th at least one hour before class

Case Study Background

Streets – especially in urban areas – serve as far more than simple conduits of vehicular traffic. They are a place for pedestrians and bicyclists; they are a place for children to play and learn; and they are part of the community as a livable and healthy environment. Trees can play a significant role in these functions. The research points to street trees being associated with a better pedestrian environment, reduced urban head island effects, less drainage infrastructure as well as a host of other social, environmental, and even economic benefits (Burden 2006, Ewing and Dumbaugh 2009). They seem to be beneficial in most every way except one… road safety.

The national safety data suggests that car/tree collisions account for more than 4,000 fatalities and 100,000 injuries in the U.S. each year. So while traffic engineers acknowledge that trees can be an asset, they also point out that trees are the "single most commonly struck objects in serious roadside crashes" (FHWA 2006). To remedy this issue, traffic engineers prefer that trees and other "fixed-object hazards" be located a safe distance from the roadside. This area where fixed-object hazards are minimized is called the "clear zone," which has been standard design practice since the 1967 AASHO[1] publication of Highway Design and Operational Practices Related to Highway Safety, which cited the need for a 6-meter (19.7') clear zone without any trees larger than 4" caliper (AASHO 1967). Soon thereafter, the recommended lateral clearance increased to 9-meters (29.7') and explicitly included both rural and urban locations. While today's traffic engineers acknowledge that trees on low-speed residential streets "do not usually present the same problems as trees near high-speed roads and highways" and recognize that urban right-of-ways are often extremely restricted, the 2011 AASHTO Roadside Deign Guide continues to encourage clear zone application wherever practical. The images at the top of the next page depict what would be considered "safe" and "unsafe" roads according to engineering guidelines.

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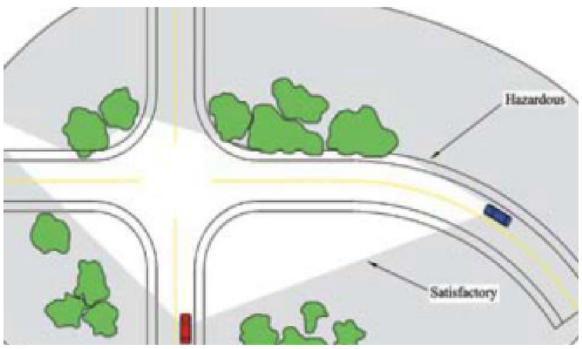
[1] AASHO, or the American Association of State Highway Officials, was the original name of present-day AASHTO, author of the "Green Book" and also known as the American Association of State Highway and Transportation Officials

"Safe"

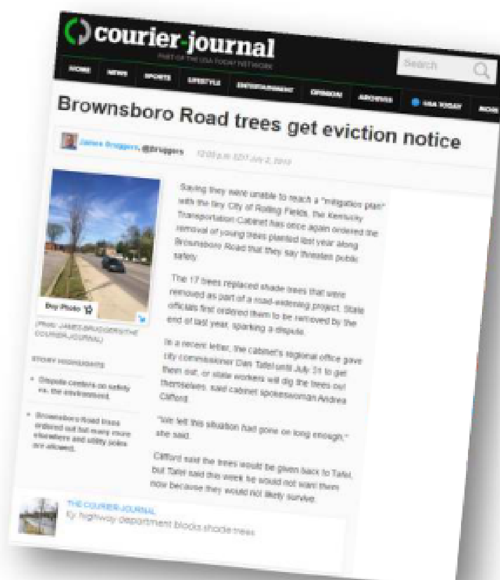
"Unsafe"



"Satisfactory" and "Hazardous" Intersection Treatments (Eck and McGee 2008)

This line of thinking also extends to intersections where good "sight distance" is considered a safety benefit. Sight distance refers to the length of roadway visible to a driver. At intersections, the thinking is that the driver should have an unobstructed view of the intersection as well as along the intersecting streets so as to anticipate and avoid potential collisions. The views along the intersecting streets are known as the approach sight triangles. In terms of tree placement, the figure to the left shows what would be a "satisfactory" and "unsatisfactory" sight distance triangles for the car approaching the intersection.

Despite standard design practice, the research remains conflicted over the true relationship between street trees and road safety (Zeigler 1986, Turner and Mansfield 1989, Dumbaugh 2005, Gattis 2005, Ivan et al. 1999, Naderi, Kweon, and Maghelal 2008, Ossenbruggen, Pendharkar, and Ivan 2001, Wolf and Bratton 2006). Even with this lack of consensus, municipalities continue to cut down trees in the name of safety improvements (see recent article to the right about safety "mitigation plan" shown for Louisville, KY).



courier-journal

Brownsboro Road trees get eviction notice

Saying they were unable to reach a "mitigation plan" with the tiny City of Rolling Fields, the Kentucky Transportation Cabinet has once again ordered the removal of young trees planted last year along Brownsboro Road that they say threaten public safety.

The 17 trees replaced shade trees that were removed as part of a road-widening project. State officials first ordered them to be removed by the end of last year, sparking a dispute.

In a recent letter, the cabinet's regional office gave city commissioner Dan Tafel until July 31 to get them out, or state workers will dig the trees out themselves, said cabinet spokeswoman Andrea Clifford.

"We felt this situation had gone on long enough," she said.

Clifford said the trees would be given back to Tafel, but Tafel said this week he would not want them now because they would not likely survive.

The goal of this case study assignment is simple: **let's try to shed light on the true relationship between street trees and road safety outcomes.**

Assignment Overview

This case study project will have you investigate road safety with respect to differences in street or intersection design, and more specifically, trees. Students will be divided into teams of three. Each team will be tasked with:

- Conducting additional background research regarding street trees in general, their connection to road safety, and the underlying thinking behind engineering concepts such as the "clear zone" and/or "sight distance"
- Selecting three streets or intersections worth studying
- Collecting quantitative and qualitative data for these streets or intersections and the surrounding neighborhoods
- Analyzing the data in an attempt to compare safety outcomes against differences in street trees while controlling for as many other factors as possible
- Drawing appropriate conclusions that speak to the issue at hand in terms of the implications for engineers, planners, and municipalities

One of the most difficult parts of this case study will be selecting the streets or intersections. While the above list places site selection prior to data collection, controlling for confounding factors will require some preliminary data collection first. For example, it might be preferable for the streets or intersections you study to have similar traffic levels (which is useful for calculating risk). While collecting your own data is more than appropriate, initially consulting some existing traffic data, such as the following, would probably be worthwhile:

Examples of Traffic Count Data

- DRCOG interactive map: http://gis.drcog.org/trafficcounts/
- Denver data: http://data.denvergov.org/dataset/city-and-county-of-denver-traffic-counts

It would also be good to make sure your street segments or intersections have enough crashes from which to make valid inferences. If you select low-traffic, residential streets or intersections that have seen relatively few crashes, then it might be difficult to speak to differences in safety outcomes, even if you have a decade of crash data. On the other hand, for streets with high traffic volumes and significant crash numbers, then you might be able to conduct a good analysis with only a year or two of crash data. Here are some initial crash data sources:

Example of Crash Data

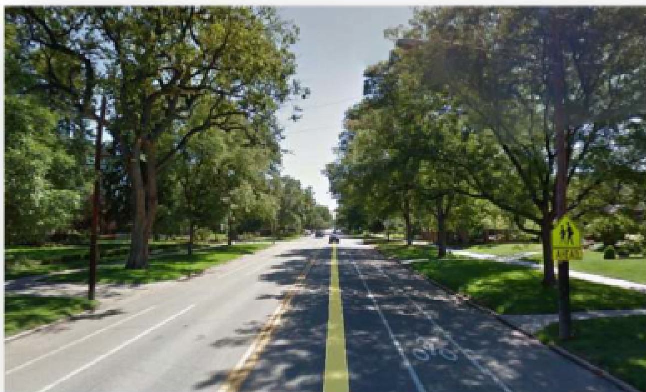
- Nine years of DRCOG regional crash data: http://gis.drcog.org/datacatalog/search/node/crash%20data%20points
- Five years of Denver crash data: http://data.denvergov.org/dataset/city-and-county-of-denver-traffic-accidents

You will want to select locations with drastic differences in their street trees, which you could initially assess qualitatively, but you could also consult the recently released tree inventory that was collected for the City and County of Denver using GPS:

Tree Data

- http://data.denvergov.org/dataset/city-and-county-of-denver-tree-inventory

With regard to trees, there is the issue of placement with respect to the clear zone (i.e. where the tree is physically located) as well as what sort of risk is associated with that tree (which might be a function of tree trunk size or caliper). Concerning road safety, you may also need to consider the tree canopy because it might influence driver behavior just as much, if not more, than where the tree trunks are physically located. For instance with the images below, taken on the same Denver street less than a mile apart, these street segments feel like they would function very differently.



Montview Boulevard in Park Hill

Montview Boulevard less than 1-mile to the East

Supplementary Data

Beyond measuring differences in safety, trees, and traffic levels, you will also need to account for:

- Differences in street or intersection design (e.g. # of lanes, street widths, size of corner radii, crossing treatments, bike lanes, medians, sidewalks, on-street parking, etc.);
- Land uses (e.g. type, setback, etc.)
- Neighborhoods (street network design, socio-demographic/socio-economic differences)
- Other concerns such as vehicle speeds

Vehicle speed is particularly important as more trees could induce lower speeds, and in turn, better safety outcomes. Please note that I have both radar guns and traffic counters (both vehicle and bike) available to borrow.

If a group wants to compare the issue of street trees and safety at the neighborhood level (instead of at the street/intersection level), I would be open to discussing this as a possibility.

Deliverables

Every group should produce the following:

1. A final report:
    - There are no minimum or maximum lengths with the report, although ideally it would be less than 10 pages of single-spaced text or 20 pages of double-spaced text (not including pictures, data, tables, or figures)
    - Please cite and reference all sources properly
2. A final presentation:
    - In class on March 14th (no more than 20 minutes per group)

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MARCH 14, 2016

CASE STUDY 1: STREET TREES AND ROADWAY SAFETY

SUSTAINABLE TRANSPORTATION – CVEN 5633

Executive Summary

This case study attempts to find a correlation between street trees and safety by analyzing the crash rates of three Denver street segments with varying tree coverage. Federal Boulevard was identified as the low tree coverage street, Alameda Avenue as the medium tree coverage street, and University Boulevard as the high tree coverage street. Other characteristics, such as measured and posted speed limits, average daily traffic volumes, and cross sections were considered as part of this case study to ensure tree coverage alone impacted crash rates. Through the analyses, it was determined that tree coverage has no direct correlation to roadway safety, and the student team believes this is a direct result of improperly selecting street segments in this case study. Further analysis is recommended.

Introduction

The purpose of this report is to examine the relationship between street trees and safety, drawing conclusions that relate to the work of planners, engineers, and municipalities. To conduct this analysis, the student team selected three Denver streets that had many similar characteristics, but differed in tree coverage. This allowed the student team to draw conclusions about tree canopy and roadway safety while holding constant as many other variables as possible. The following one-quarter mile street segments were studied.

- Federal Boulevard from Dartmouth Avenue to Bates Avenue (low tree coverage)
- Alameda Avenue from Broadway Street to Logan Street (medium tree coverage)
- University Boulevard from Louisiana Avenue to Mississippi Avenue (high tree coverage)

In addition to number of trees present in each segment, the student team collected the following data for each street: speed limit (posted and measured), average daily traffic volume (ADT), cross section, crash rate, tree setback, tree diameter distribution, land use, and curb cuts. The student team compared the three street segments using this information and drew conclusions about street trees and roadway safety.

The full results and recommendations of this case study are provided within this report.

Street Tree Background

The majority of the United States' population lives in cities where hardscape urbanism is disconnected from nature and what little greenery exists is under threat. "Tree cover in cities is constantly changing due to various natural and anthropogenic forces such as tree growth and tree mortality, and development and air pollution, respectively" (Nowak & Greenfield, 2012, p. 21). Nowak and Greenfield (2012) found that tree cover in urban areas of the United States is on the decline at a rate of about 7,900 hectares per year or four million trees per year while rates of impervious surfaces increase (p. 21). While urban planners would claim that the loss of urban street trees denies residents of their social, environmental, and economic benefits, traffic engineers insist that their removal promotes road safety for motorists.

According to the Federal Highway Administration (FWHA), what makes street trees hazardous are their size and location with respect to vehicle traffic; trees larger than four inches in diameter can be a hazard to a vehicle and the closer trees are to a travel lane, the more likely a vehicle is to strike them (FHWA, 2007). Guidelines suggest that removal should be based on potential crash frequency and severity. Traffic engineers should first prioritize trees closest to the road, trees in critical locations such as curves and intersections, and trees that have previously been struck. Trees should be cut close to the ground so that no fixed object or snagged hazard remains. Dead or leaning trees within road right-of-way should similarly be disposed of. Also, where trees provide shade for waterways, the trees should be mitigated to safer locations (FHWA, 2007).

Highway and street agencies are concerned with safety and take responsibility for reviewing roads and rights-of-way, identifying hazards, and making street conditions safer. In addition to trees, grass, weeds, and brush can also obstruct a driver's view of traffic control devices, approaching vehicles, wildlife and livestock, pedestrians, and bicycles. While traffic engineers "recognize the sensitivity of removing individual trees," they recommend still doing so to maintain sign visibility, clear sight lines, and side road visibility because "no one will be tempted to try to save a beautiful, but hazardous, tree in the roadway clear zone" (FHWA, 2007).

To present a case and defend the value of street trees, urban planners and urban designers point to the substantial benefits of urban greenery. This includes environmental, social, and economic benefits:

Social

Street trees are an urban amenity that both beautifies neighborhoods and provides city dwellers with a connection to nature and a sense of place. Recently, researchers have conducted and reviewed studies that explored the valuable relationship between nature and public health. According to Danish researchers for the International Federation of Parks and Recreation Administration:

> "Nature and green spaces contribute directly to public health by reducing stress and mental disorders, increasing the effect of physical activity, reducing health inequalities, and increasing perception of life quality and self-reported general health. Indirect health effects are conveyed by providing arenas and opportunities for physical activity, increasing satisfaction of living environment and social interactions, and by different modes of recreation . . ." (as cited in Benfield, 2014).

Whether in parks, yards, or along roads, the presence of trees incorporates nature into the built environment in such a way that supports livability within it.

In addition to creating an attractive space - and contrary to traffic engineers' theories - urban trees contribute to public and traffic safety. Walking environments are made safer and more pleasant when street trees are present because they create a buffer between traffic and pedestrians. As a result, more activity can be found on the street where pedestrians are joined by others, and together they form a network of local surveillance and increased security. "Urban street trees also contribute to reduced and more appropriate traffic speeds by creating vertical walls that frame streets and provide a defined edge helping to guide motorists' movement and assess their speed; speed differentials between treed and non-treed portions of a street are between three and 15 miles per hour" (Burden, p. 3).

Environmental

Urban trees are an asset that hosts countless environmental benefits including carbon sequestration, canopy coverage, and runoff absorption. With global concerns over the increasing rate of greenhouse gases, trees are an essential solution. Trees facilitate carbon sequestering where "one acre of forest absorbs six tons of carbon dioxide and puts out four tons of oxygen" (Benfield, 2012). Further, the proximity of trees also matter. "Trees located near roads absorb 9 times more pollutants than more distant trees, converting harmful gasses back into oxygen and other useful and natural gases" (Burden, p. 6). Additionally, trees can reduce particulates by 9% to 13% and reduce the amount of dust reaching the ground by 27% to 42% (Benfield, 2012). Subsequently, the air quality of areas with greater tree coverage are improved as well as the health of residents, animals, and surrounding agricultural lands (Burden, p. 6).

Furthermore, trees provide a canopy that offer rain, sun, heat, and skin protection (Burden, p. 5). Urban areas without adequate tree coverage often suffer from urban heat island effect where built areas are hotter than rural areas. This can be attributed to "streets and parking lots which are known to increase urban temperatures by three to seven degrees. These temperature increases significantly impact energy costs linked to cooling" (Burden, p. 6). "The net cooling effect of a young, healthy tree is equivalent to ten room-size air conditioners operating 20 hours a day. If an individual were to plant a tree today on the west side of a home, in 5 years their energy bills should be 3 percent less. In 15 years the savings will be nearly 12 percent" (Benfield, 2014).

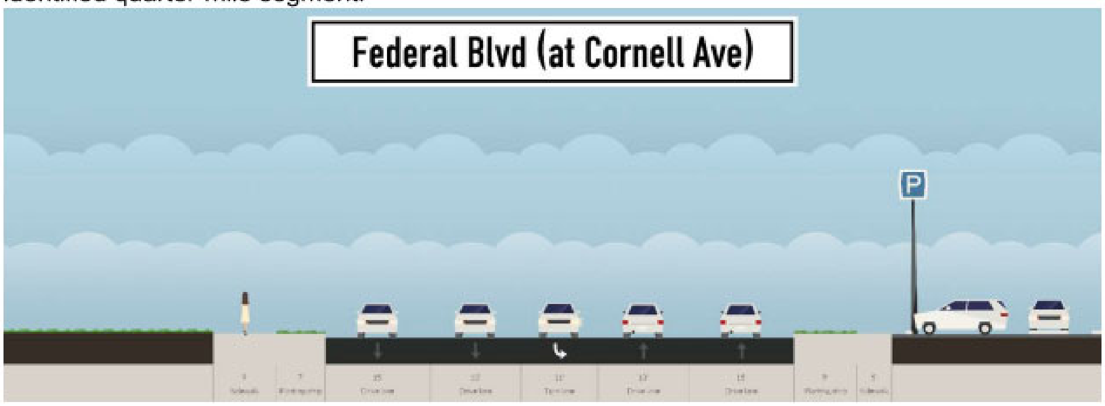
Many urban areas face stormwater management challenges due to inadequacies in their stormwater and wastewater systems. Trees alleviate the demand on drainage infrastructure in two ways. First, trees absorb the first 30% of most precipitation through their leaf system, allowing evaporation back into the atmosphere; this moisture never hits the ground. Second, the root system of trees can absorb and hold up to 30% of water that reaches the soil which is then transpired back to the air (Burden, p. 5). To quantify how much a city could save by using trees to intercept rainfall, Soares et al. (2011) used a numerical interception model. The study calculated the average annual cost of controlling stormwater runoff and estimated volume of stormwater runoff in Lisbon, Portugal (p. 73). Soares et al (2011) found that Lisbon's street trees' interception of rainfall was associated with stormwater runoff reduction valued at $1.97 million (p. 75). Urban trees are vital to stormwater management, reducing flooding risk, and saving cities money on drainage infrastructure demand.

Economic

Dan Burden's "Urban Street Trees: 22 Benefits Specific Applications" has been widely cited for its contribution to the case for street trees. He notes the monetary value of trees and states, "For a planting cost of $250-600 (includes first 3 years of maintenance) a single street tree returns over $90,000 of direct benefits (not including aesthetic, social and natural) in the lifetime of the tree" (p. 2). The Council of Tree and Landscape Appraisers found that property values benefit from the presence of mature trees which can often have an appraised value of between $1,000 and $10,000 (as cited in *Benefit of Trees*); an increase in home values further translates to higher property taxes. Arbor National Mortgage & American Forests cited a study where "83% of realtors believe that mature trees have a 'strong or moderate impact' on the salability of homes listed for under $150,000; on homes over $250,000, this perception increases to 98%" (as cited in *Benefit of Trees*). Street trees are also responsible for creating a beautiful, appealing, and inviting image of a city. The Arbor Day Foundation explained, "Trees can be a stimulus to economic development, attracting new business and tourism. Commercial retail areas are more attractive to shoppers, apartments rent more quickly, tenants stay longer, and space in a wooded setting is more valuable to sell or rent" (as cited in *Benefit of Trees*). "Businesses on treescaped streets show 12% higher income streams, which is often the essential competitive edge needed for main street store success" (Burden, p. 5). Taken together, it becomes clear that the monetary cost of street trees are far outweighed by the incredible benefits that can be recaptured by the local economy.

Site Selection

Picking three street segments was among the most challenging parts of this case study. The student team decided to focus on arterials, which narrowed down the options quite a bit. University Boulevard was an obvious choice, as it is among the few arterials in the city that has a large tree canopy. Federal Boulevard is on the other end of the spectrum; the street is sparse and has very few trees. Alameda Avenue was determined to have tree coverage somewhere in the middle. Below are the cross sections for each of these streets at an intersection within the identified quarter-mile segment.



Federal Boulevard has two through-lanes in each direction with a southbound left turn lane. On the west side of the street is a college campus with a big open space adjacent to the street. There is a parking lot on the east side of the street. The public right-of-way (including grass sections and sidewalks) is 97 feet. The outermost lanes are extremely wide at 15 feet, and lane width decreases toward the center of the street.

Similar to Federal Boulevard, Alameda Avenue has two through-lanes in each direction with an eastbound left turn lane. The sidewalks are adjacent to the street, and the tree lawns separate the sidewalk from the adjacent lots. The tree setback is approximately 12 feet. The lanes are significantly narrower than those at Federal Boulevard. Each lane is 10 feet wide, except the turn lane that is 9 feet. The total right-of-way, again including sidewalks and tree lawns, is 81 feet. The north side of the street has a parking lot, and the south side of the street has retail uses.

University Boulevard also has two through-lanes in each direction (all 11 feet wide), but does not have a turn lane. The tree lawns separate vehicular traffic from the sidewalks, and tree setback is approximately 8 feet. While the sidewalks are only 4 and 5 feet wide, the tree lawns are 16 feet, providing a large buffer from heavy roadway traffic. The total right-of-way is 85 feet. The west side of the street has single-family homes, and the east side of the street is also mostly residential with one institutional land use, namely a church.


Federal Boulevard


Alameda Avenue

Data Collection

Field data collection occurred on March 8, 2016, between 2:30 and 3:45pm. The first site visited was Federal Boulevard from 2:30 to 2:40. During this time, 57 speeds were measured, however there were two outliers (89 and 106 mph) which were removed. Of the 55 recorded speeds, the slowest was 35 mph and the fastest was 59 mph. The sample of vehicle speeds demonstrated a mean of 42.1 mph, mode of 39 mph, and median of 42 mph. The posted speed limit was 40 mph. During the site visit, there were only a few pedestrians and no bicyclists observed. Additionally, sidewalks were varying in condition. Along the college campus on the west side of the street, there were good sidewalks but just across the street, there was a mixture of good and poor quality sidewalks.

University Boulevard was the second site visited. Data collection occurred between 3:05 and 3:15. 49 speeds were recorded with one outlier of 73 mph removed. The slowest recorded speed was 25 mph and the fastest speed was 38 mph. Basic statistics shows the mean as 31.4 mph and mode and median of 32 mph. The posted speed limit along the University Boulevard section was 30 mph. The trees along the site were large, mature trees that served as a buffer between the road and the sidewalks. Few pedestrians and bicyclists were observed.

Alameda Avenue was the final site visited between 3:34 and 3:44. 26 vehicle speeds were measured with no outliers observed. The slowest recorded speed was 25 mph and the fastest was 36 mph. The mean was 28.7 mph and mode and median were 27 mph. Posted speed limit was 30 mph. This site was the only one where the average speed was less than the speed limit. Many pedestrians were observed and there were good sidewalks along the street. There was heavy mixed use and traffic lights along the site which may have attributed to slower speeds.

A summary of this data can be found below. The average speeds exclude the outliers noted above, but the range includes them.

	Alameda Avenue	University Boulevard	Federal Boulevard
Posted Speed Limit (mph)	30	30	40
Average Speed Limit (mph)	29	31	42
Range (mph)	25-36	25-73	35-106

Data Analysis

The project team used ArcGIS to determine the remaining data used in this case study. The tables found within this section summarize the full results of these analyses.

	Alameda Avenue	University Boulevard	Federal Boulevard
ADT	27,000	32,000	26,000
Number of Curb Cuts	8	6	15
Number of Vehicular Crashes (2010-2015)	170	65	20
Number of Trees	24	54	3
Tree Setback (feet)	12	8	N/A

The average daily traffic volumes for the three segments are nearly equivalent to one another. Federal Boulevard has the lowest at 26,000 vehicles, and University Avenue has the highest at 32,000 cars. All three streets have high vehicular volumes.

The number of curb cuts is an important indicator for the level of safety of each street. This measurement contributes to the number of points of conflict in each segment, as vehicles are entering and exiting the roadway. Federal Boulevard has the most with 15 curb cuts, and University Avenue has the fewest with just six curb cuts in the quarter-mile section. This indicates that Federal Boulevard has high mobility and high access, while Alameda Avenue and University Avenue have high mobility and low access.

The number of vehicular crashes is where a major difference among the street segments can be seen. Alameda Avenue had 170 vehicular crashes from 2010-2015 on this quarter-mile segment alone. Of these, 40 were hit and run crashes. University Boulevard had 65 total crashes in the same time period, and Federal Boulevard had just 20 crashes. Using standard FHWA crash rate calculations, the following table shows crash rates for each segment per million vehicle miles travel

	Alameda Avenue	University Boulevard	Federal Boulevard
Accident Rate per Million Miles Traveled	1380	445	169

The land use varies slightly by street segment. Commercial, residential, and institutional land uses are present on both Alameda Avenue and Federal Boulevard. University Boulevard does not have any institutional land uses within the selected segment. Commercial is the most prevalent along Alameda Avenue and Federal Boulevard, and residential is the most prevalent along University Boulevard. Alameda Avenue and Federal Boulevard both have a good mix of land use, while University Boulevard is almost entirely residential. Parks and open space, industrial, and agricultural land uses were absent from these segments.

Land Use	Alameda Avenue	University Boulevard	Federal Boulevard
Commercial	54%	0%	47%
Institutional	7%	10%	40%
Residential	39%	90%	13%
Total	100%	100%	100%

The following table shows the distribution of tree sizes along the three roadway sections. Not only does University Boulevard have the greatest number of trees of the three segments, but it also has the widest range of tree diameters. This implies that there is greater tree diversity along University Boulevard, the city has continuously planted for many years (meaning the trees are of differing ages), or both. All of these options improve ecosystem health, and thereby increase longevity of the planted trees.

Diameter (inches)	Alameda Avenue	University Boulevard	Federal Boulevard
0 to 6	0	6	1
6 to 12	14	18	2
12 to 18	9	11	0
18 to 24	0	3	0
24 to 30	0	9	0
30 to 36	1	5	0
36 to 42	0	2	0
Total	24	54	3

Conclusion

The data collected in this study disproved a number of operating assumptions of the student team. The segments were selected to have similar typological variables, with an importance placed on similar ADT, number of lanes, posted speed limits, and roadway classifications – while have a high, medium, and low density of street trees. The team expected to see the correlation between lower observed vehicle speeds and higher density of trees lining the roadway with a lower crash rate. As seen in the analysis, Federal Boulevard has the lowest tree density, highest observed vehicle speeds , yet lowest crash rate. While Alameda had the highest crash rate by a large margin, it was thought that this was due to the three signalized intersections contained within that segment. However, even when factoring out the crashes at those intersections, Alameda still had a higher crash rate than Federal Boulevard, while have having a lower rate than University Boulevard (seen in the table below).

	Alameda Avenue (adjusted)	University Boulevard	Federal Boulevard
Accident Rate per Million Miles Traveled	300	445	169
Number of trees	24	54	3

This adjustment would indicate the position of the highway engineer is correct, and that a lower number of street trees correlates to a safer roadway. However, it is the student team's position that these results do not show a direct correlation between roadway safety and absence of street trees, rather the results are a function of a limited collection of data. Further analysis is recommended.

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14.1.2 Example of Student Output No. 2 from CVEN 5633

March 14, 2016

Case Study No. 1 – Street Trees & Safety

Alameda Avenue

In our increasingly urban way of life, it is not difficult to understand why green spaces and trees in the urban environment are desirable. People seek out parks and green spaces to walk, run, play and spend time with family and friends. People want to live near these spaces; property values in cities rise in proximity to open green spaces (Harnik and Welle, 2009). Research demonstrates the substantial psychological benefits people gain by spending time in nature, from reduced stress and depression (Bratman et al., 2015), to increased cognitive functions in children (Dadvand et al., 2015). Trees along our roadways have been shown to have similar positive impacts. A 1998 study found that drivers commuting along green and natural roadsides report lower stress and anxiety compared to those commuting along non-natural settings (Parsons et al., 1998).

Street trees provide a safe and inviting pedestrian environment. They form a contour of our sidewalks and roads and they provide shade from the hot sun. They also provide significant environmental benefits to urban areas, including, for example, their cooling effect, their role in carbon dioxide absorption, water retention and oxygen production (Benfield, 2014). As noted in Dan Burden's 2006 article, there is even evidence of reduced road rage on tree-lined streets (Burden, 2006). The list goes on. Whether street trees contribute to or reduce road safety is, however, an ongoing question with opposing views and recommended actions.

While the Federal Highway Administration (FHWA) recognizes the environmental and social value of street trees, the organization argues these benefits must be balanced with safety concerns. FHWA reports that trees are the objects most commonly hit by vehicles, causing over 4,000 fatalities and 100,000 injuries annually (FHWA, 2011). Others argue the likelihood of car-to-tree crashes are more characteristic of rural or higher speed roads, not urban streets. Bratton and Wolf, for example, conducted a study of traffic accidents in urban and rural areas across the US. They found the average speed at the time of a car-to-tree crash was 48 miles per hour and that less than 1% of car-to-tree crashes occurred in urban areas (Bratton and Wolf, 2005).

Nonetheless, FWHA and the American Association of State Highway and Transportation Officials (AASHTO) have long recommended highway agencies follow clear zones and sight distance guidelines to prevent injuries and fatalities due to car-to-tree crashes.

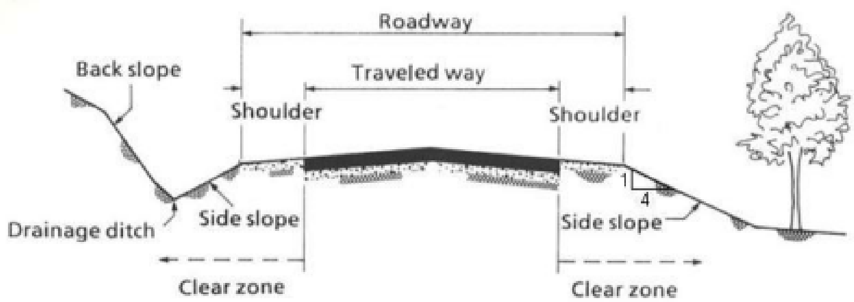
Clear Zones and Slight Distance

According to FWHA (2015), a clear zone is, "the total roadside border area, starting at the edge of the traveled way, available for safe use by errant vehicles." Tress and other objects should be a distance from the roadside. FHWA notes that the width of the clear zone depends on speed and road geometry. The AASHTO

1

provides more specificity here; however its guidelines have changed over the years. The 1967 AASHTO Highway Design and Operational Practices Related to Highway Safety recommended a 6-meter clear zone. According to Marshall (2015, page 2), in the 1970 AASHTO, "the lateral clearance increased to 9-meters and explicitly included rural and urban areas". Accounting for the variation of road types, the 2001 AASHTO clear zone reports a minimum of 3-meters can be feasible on low-speed, low-volume roadways (pg. 417). Clear zones continue to be recommended and were included in the 2011 AASHTO publications.

Clear zone illustration



FHWA, 2015. Clear Zone and Horizontal Clearance

Slight distance refers to, "the length of roadway visible to a driver" (AASHTO, 2001). The literature commonly separates this concept into three slight distance types: intersection, passing and stopping sight distance. For intersection slight distance, the driver should have a clear view of the intersection while approaching and departing from the intersection. These are referred to as approach and departure sight triangles (AASHTO, 2001). A driver approaching an intersection and a driver stopped at an intersection require adequate unobstructed sight distance to safely drive through the intersection.

Stopping sight distance is the sum of two measures: the distance traveled from the moment a driver pushes the brake after seeing an object that requires stopping, and the distance needed to stop a car from when the driver pushed the brakes. These are referred to as "brake reaction" and "braking" distance, respectively (AASHTO, 2001). AASHTO 2001 recommends enough distance for 2.5 seconds of brake reaction time and 3.4 seconds for braking time on the average highway. Passing sight distance, applicable to roadways with two or more lanes, is the sight distance needed for drivers to assess the ability to safely pass and to complete the pass. Given the variation in driver behavior and impact that has on passing, AASHTO's measurement makes a number of assumptions and takes into account the majority of drivers' behaviors.

These concepts largely developed due to the sharp rise of vehicular injuries and fatalities in the 1960s. To help address this rise, a Congressional hearing on road safety took place in 1966. According to Marshall (2015), one of the outcomes of the hearings appeared to be a shift away from public awareness campaigns and driver behavior to the establishment of new engineering standards to prevent injuries and fatalities. Clear zone guidelines were developed the following year in the 1967 AASHTO.

Due to the emphasis on these standards nationally over the last few decades, many state and local agencies have followed suit. The Colorado Department of Transportation's Strategic Highway Safety Plan (2014) recommends the use of current engineering standards, including clear zones, to improve road safety where fatalities and injuries are occurring. The City of Rolling Fields, Kentucky ordered the removal of trees on a road planned for a road widening project to improve driver visibility (Bruggers, 2015). The City argued that although the environmental impact of removing the trees was considered, their action was done in the name of public safety.

With this in mind, is it safer to remove street trees? Is the risk of injury or fatality so high it removes all other benefits? Or is speed simply not something we are willing to relinquish? The driver's comfort and ability to drive with reasonable speed seems to be the focal point of these actions and FHWA and AASHTO guidelines. The answer to a tree-lined street has not been to reduce speed, but to remove what is causing the driver to feel speed should be reduced. Certainly, part of the challenge is the variability of roadways in the US and the challenge of uniformly applying policies to high-and-low speed and urban and rural roads. If the vehicle and its speed was not a central factor in setting these policies, trees may have been encouraged on many streets. What does the research tell us?

Street Tree and Road Safety Research

Many of the early research studies on the topic supported the connection between the proximity of trees to the roadway and vehicular crashes. As reported by Marshall (2015), Tuner and Mansfield (1989) and Zeigler (1986) measured the share of car crashes into trees that occur within a particular distance from the road. Marshall (2015) reports these studies concluded that the majority of crashes occur within 20 and 30 feet of the road, respectively. Marshall notes, however, that these early studies, do not examine whether the presence of trees themselves impact safety, they simple tell us where accidents occur.

Other more recent studies report different conclusions. A 2008 study of crashes on five arterial roads in Toronto found that crashes were between 5% and 20% lower on blocks with trees and planters (Naderi, 2008). Similarly, Mok, Landphair and Naderi (2006) conducted a study of ten road sections in Texas before and after landscaping improvements, including trees. Their study found a dramatic decline in crashes in the landscaped sections. The literature also points to the concept of risk compensation and the impact on driver behavior. As Marshall (2015) notes, "making a street feel narrower – and perhaps even feel more dangerous as well – could entice people to behave differently and perhaps more safely (pg., 3)." This is intuitive; while driving on a narrow, gravel road with poor visibility, we are forced to slow down. This street may feel dangerous but we are cautious, cognizant of our surroundings and safe.

While acknowledging the safety benefits clear zones provide, Bratton and Wolf argue they fail to, "incorporate community values and environmental amenities into design" (2005, pg.,2). Road design, they suggest, has been considered in a vacuum, without consideration of surrounding spaces and the role trees can pay in designing safe roadways. They conclude that, "While outright removal may lead to a reduction in injurious roadside accidents, it does so without taking into account the benefits trees provide or their value to communities" (Bratton and Wolf, pg.,12). With all of this in mind, this case study of Alameda Avenue will help contribute to this discussion about the relationship between street trees and road safety.

METHODOLOGY

This case study examines three street segments along Alameda Ave, an arterial road that runs east-west through metro Denver, in order to understand the impact of street trees on safety. These street segments include: Alameda between Canosa Street and Clay Street; Alameda between Bannock St and Cherokee St; and Alameda between Holly St and Ivy St. The street segments were chosen because they have similar cross sections and traffic volumes but differ in the number, placement, and size of street trees.

This case study begins with an analysis of each of the three street segments and their neighborhood contexts in order to account for other factors, in addition to street trees, that may influence safety. These other factors include street design differences (number of lanes, lane widths, medians, curb radii, etc.), land use and urban form context, neighborhood street network differences, and neighborhood demographic/socioeconomic differences.

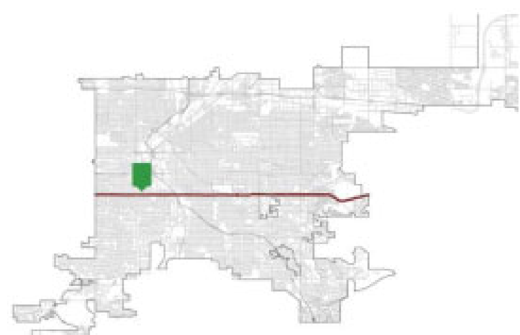
Next, this study presents data on street tree placement and tree canopy for each of the street segments, followed by crash data as well as average and median vehicle speeds. Vehicle speeds and crashes are used as indicators of street safety.

ANALYSIS

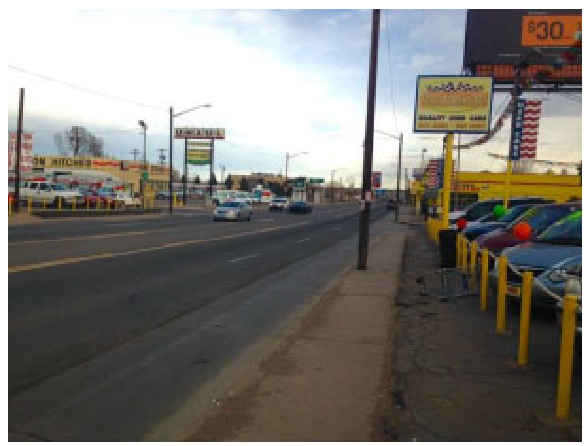
The following section presents existing conditions analysis for each of the three street segments included in this case study. Analysis is broken down by location, beginning with a summary of each location, followed by a more detailed overview of land use, neighborhood, and street design characteristics. Each section concludes with tree, speed, and crash data and findings.

Street Segment 1: Alameda Ave between Canosa Ct and Clay St

The first street segment, which had no trees, is located on an auto-oriented commercial and industrial section of Alameda Ave bordering the Valverde and Athmar Park Neighborhoods in Denver. The particular segment we chose has a relatively short block length of about 300 ft. Speed data and traffic counts were collected for eastbound traffic from a location approximately 220 feet to the east of the intersection of Alameda and Clay. Although this section had the narrowest lane widths, it had the highest vehicle speeds and crashes, which supports the hypothesis that a lack of street trees contributes to unsafe street conditions.



Looking west on the south side of Alameda

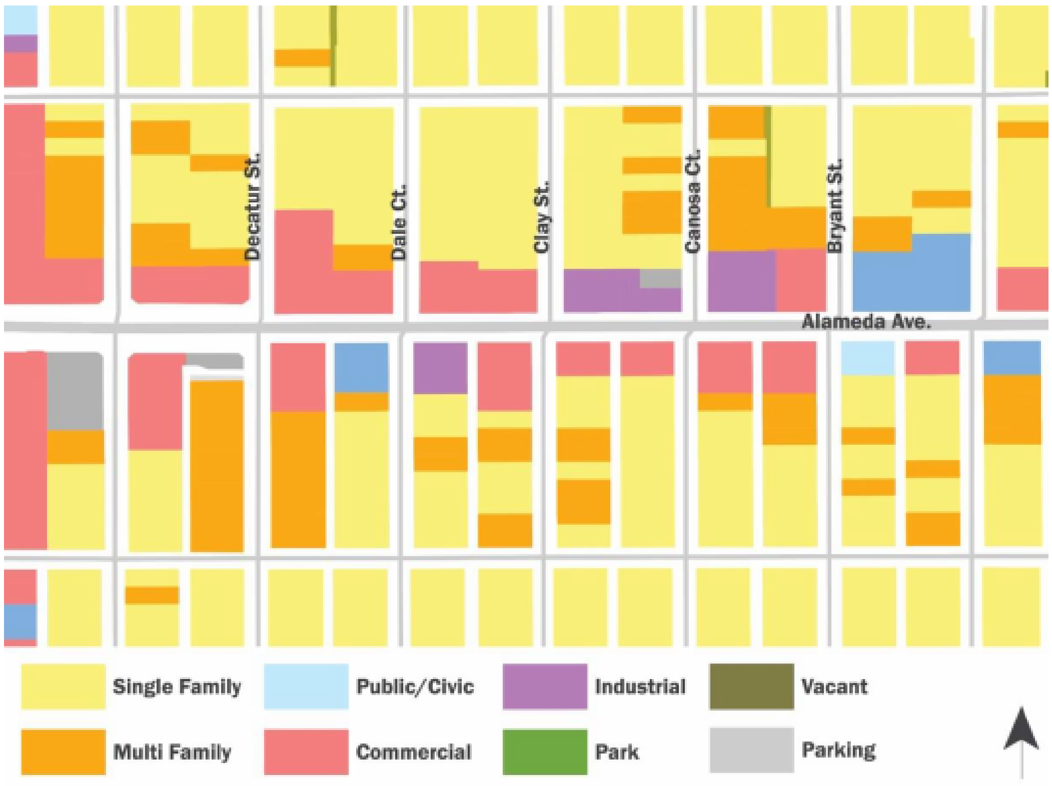


Looking east on the south side of Alameda

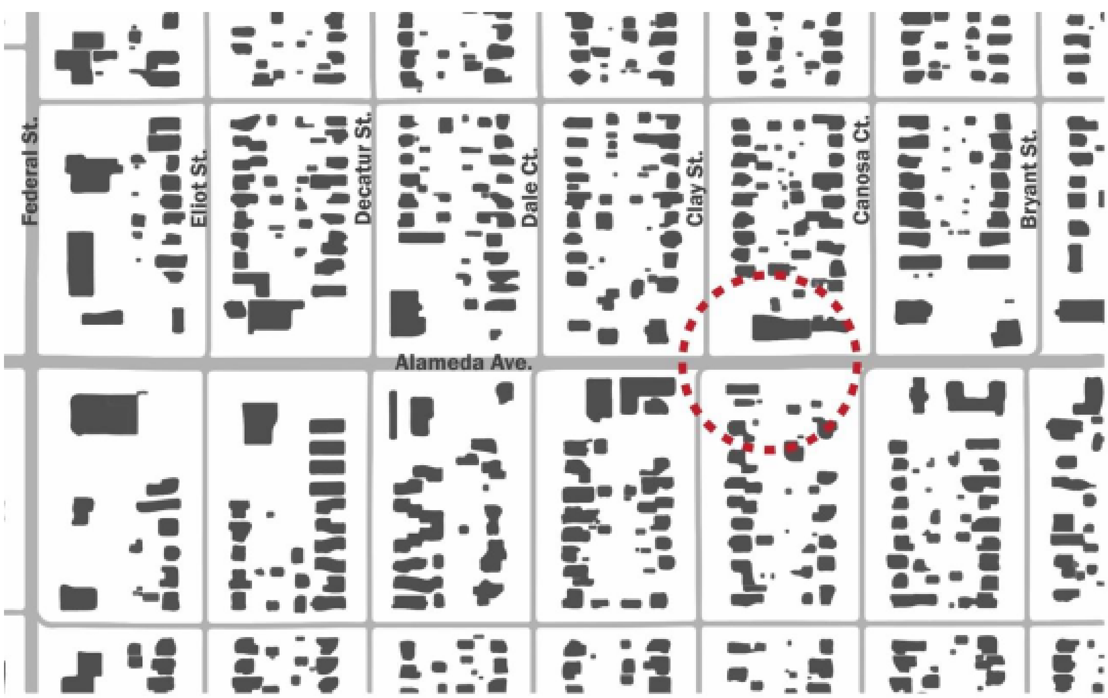
Land Use and Building Form Context

As previously mentioned, the first street segment was located along an auto-oriented commercial and industrial stretch of Alameda Ave. The block between Canosa Ct and Clay St includes a gas station and used car lot on the south side of the street and mechanic service on the north side of the street. Most buildings along this section of Alameda, including all buildings along this particular block, are set back from the street by one or two rows of parking. Building entrances, though mostly set back, are generally oriented toward Alameda.

Land Use Map



Building Figure Ground



Neighborhood Characteristics

The street network in the neighborhood surrounding Street Segment 1 is generally a rectilinear grid form with long, narrow blocks. Typical block dimensions are about 300 feet (east-west) by 620 feet (north-south).

The two census tracts bordering this section of Alameda Ave cover the Valverde neighborhood and the west half of the Athmar Park neighborhood. Data from the 2014 American Community Survey 5-Year Estimates indicate that these census tracts are generally younger, lower-income neighborhoods with much higher percentages of racial and ethnic minorities than the City & County of Denver as a whole. Single occupant vehicle mode shares for these neighborhoods are similar to Denver as a whole.

Selected Data for Census Tracts Adjacent to Street Segment 1

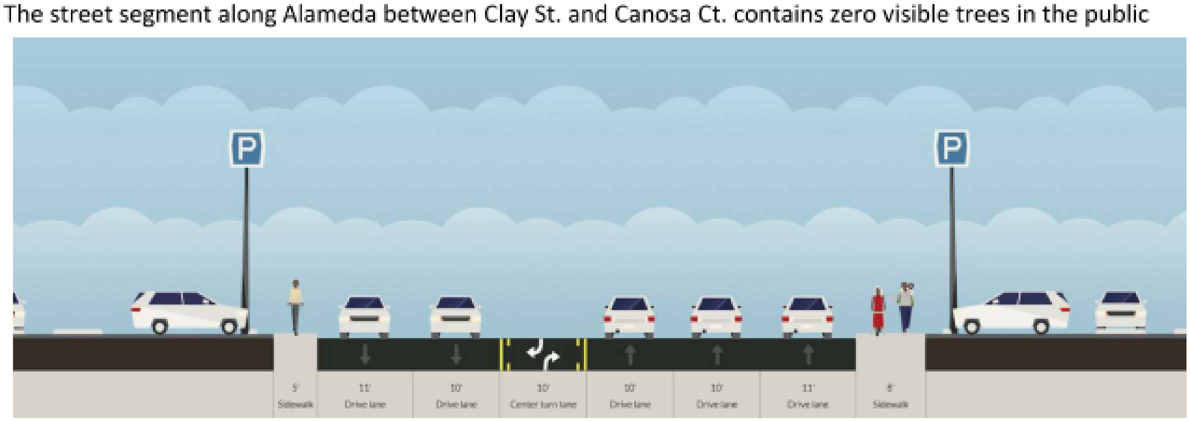
	Valverde	**Athmar Park West**	**Denver**
Median Age	28.6	32.5	34.0
Median Individual Income	$19,740	$21,369	$30,709
Percent Ethnic or Racial Minorities	85.3%	82.6%	47.1%
SOV Mode Share	71.1%	66.0%	69.7%

Street Design

The first street segment has the narrowest lane widths (10 to 11 feet), but less of a sense of enclosure due to the lack of street trees or amenity zones and the presence of auto-oriented uses on either side. Sidewalks are attached and relatively narrow. The overall right-of-way width is approximately 75 feet, and the curb-to-curb width is approximately 62 feet. A total of four driveway curb cuts (two on each side of the street) are spaced along the block, all about 30 to 40 feet wide. Despite the narrower dimensions of this street segment, it exhibited the highest vehicular speeds and crashes, which is discussed later.

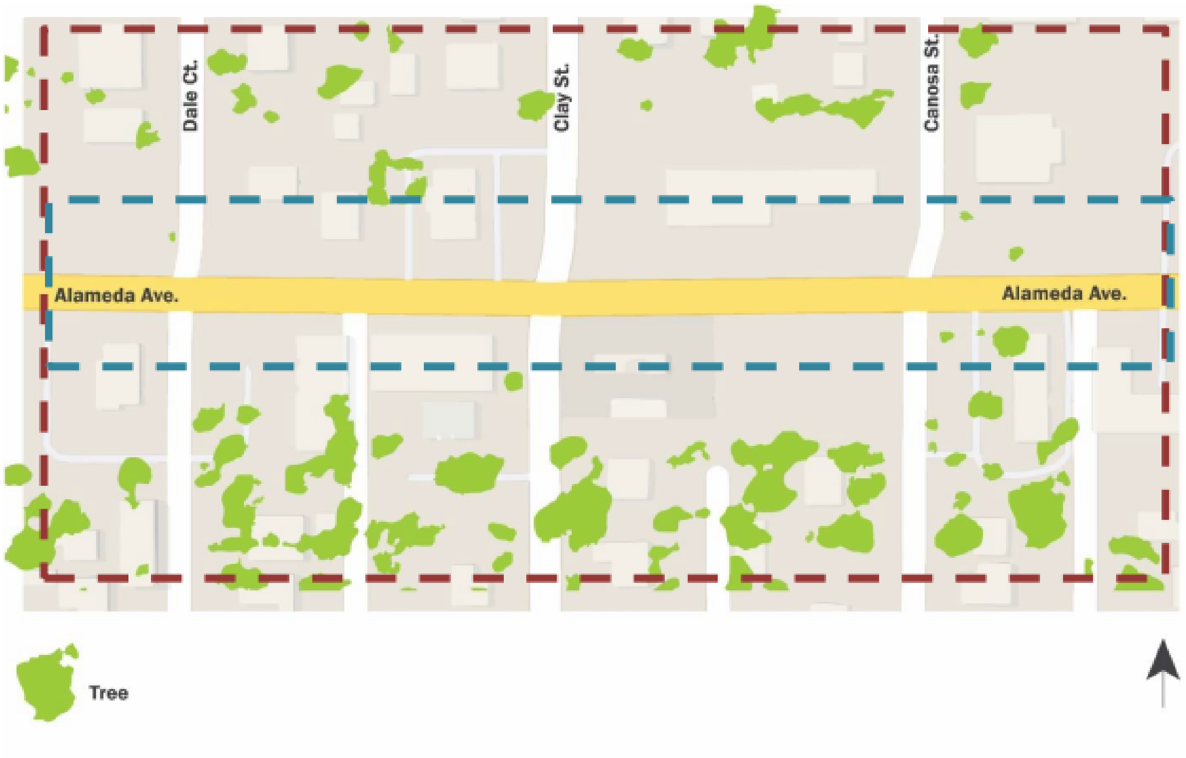
Tree Canopy/Street Trees

The street segment along Alameda between Clay St. and Canosa Ct. contains zero visible trees in the public



Alameda between Canosa Ct and Clay St, looking west right of way. Because the sidewalk directly abuts the street and the primary land uses are dedicated to commercial and industrial with surface parking lots, there is limited space available for tree lawns. The tree canopy of the blocks immediately surrounding this segment was approximately 20.5%, which is equivalent to the average canopy across the city of Denver. However, the tree canopy along Alameda Ave., the adjacent sidewalks, and street front lots between Decatur St. and Alcott St, which includes the study segment, is 0%.

Tree Canopy Map: Alameda and Clay



Canopy within surrounding blocks: 20.5%

Canopy along Alameda and adjacent frontage lawns and sidewalks: 0%

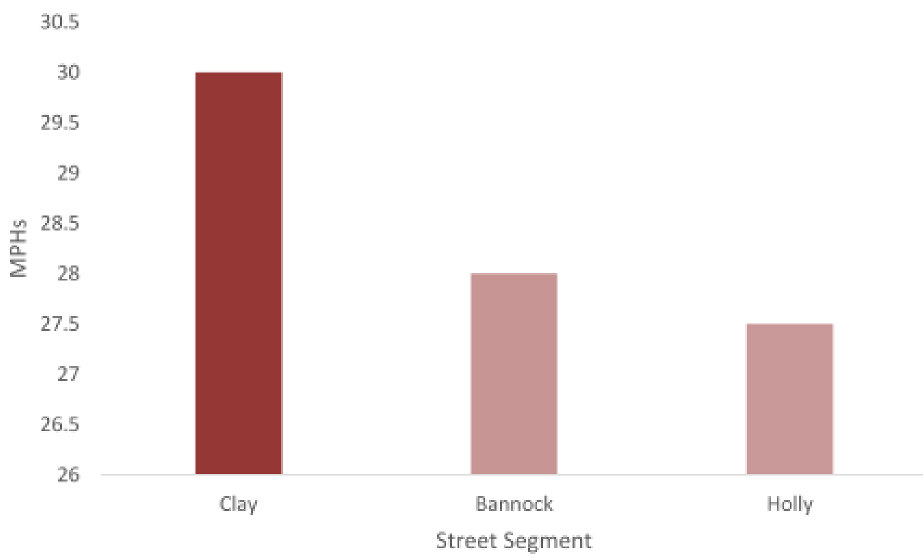
Traffic Count

The number of vehicles was counted over a period of ten minutes on a Sunday afternoon between 3:00 pm and 4:00 pm. 200 eastbound cars passed the count location (about 220 feet to the east of the intersection of Alameda and Clay) and would equate to approximately 28,800 cars per 24 hours. According to recent DRCOG traffic counts, the Alameda and Federal intersection, which is 3 blocks west, sees approximately 32,952 cars per 24 hour period. During the period of measurements, there were two bikes (both riding westbound on the sidewalk) and four pedestrians.

Vehicular Speeds

Vehicular speeds were measured over a period of ten minutes approximately 220 feet east of the Clay and Alameda stop light. Measurements occurred on a Sunday afternoon between 3:00 pm and 4:00 pm to limit the potential confounding variables, such as congestion, that impact vehicular speed. The median speed of cars along the Clay and Canosa segment was 30.00 mph with a standard deviation of 4.15. During the period of review, the highest recorded speed was 43 mph and the lowest was 20mph. The posted speed limit along this segment is 35 mph. Of the three recorded street segments, the average speed of vehicles was highest between Clay St. and Canosa Ct.

Vehicular Speed: Alameda between Canosa Ct & Clay St



Traffic Accidents

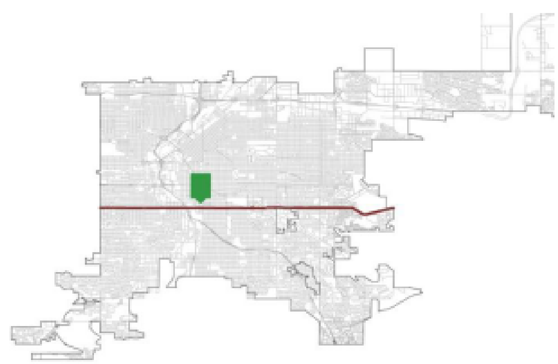
According to the DRCOG accident data between 2004 and 2012, this street segment experienced 44 accidents, approximately 5 accidents per year, with registered vehicle speeds ranging from 5 mph to 70 mph. There were no registered fatalities during this 9 year period. If around 33,000 cars pass along this street segment per 24 hour period, which equates to approximately 12,000,000 cars per year, then this segment, with an average of 4.89 crashes per year has an accident risk of .0408 per 100,000 person years. The relative risk of the Clay segment compared to the Bannock segment is 2.305, which is greater than 1, meaning the risk of driving on Alameda between Clay and Canosa is greater than the segment between Bannock and Cherokee. The relative risk of the Clay segment compared to Holly segment is 2.60 which is greater than 1, meaning the risk of driving on Alameda between Clay and Canosa is greater than between Holly and Ivy.

Traffic Accident Map: Alameda and Clay

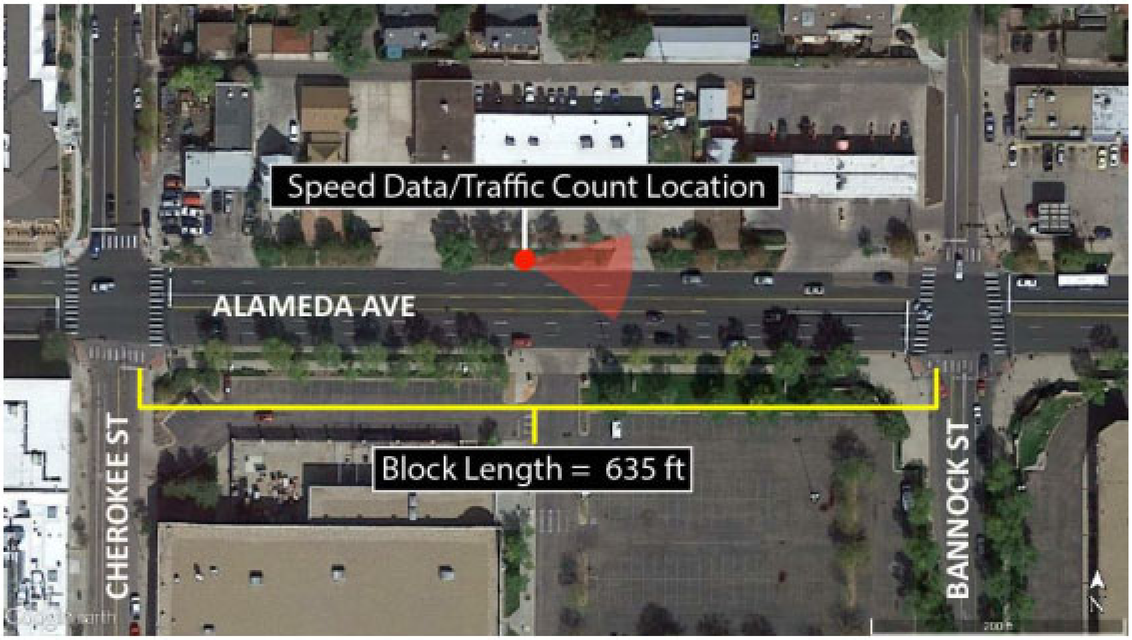
Total Accidents: 44

Accident Risk: .0408 per 100,000 person years

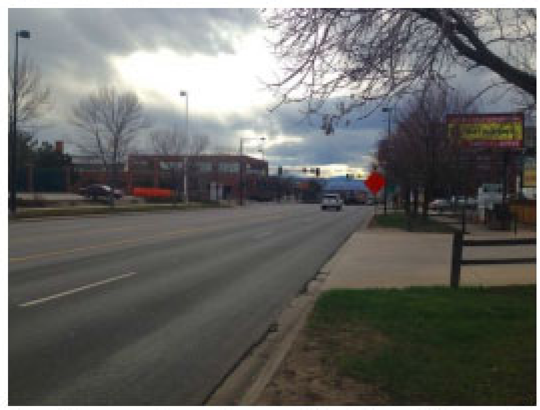
Street Segment 2: Alameda between Bannock St and Cherokee St



The next street segment, which has medium-sized street trees on both sides of Alameda Ave, is located on another mostly auto-oriented commercial stretch of Alameda within the Baker Neighborhood in Denver. The particular segment we chose has a relatively long block length of about 625 feet. Speed data and traffic counts were collected for westbound traffic from a location approximately 320 feet to the west of the intersection of Alameda and Bannock. Street tree presence, lane widths, as well as vehicle speeds and crashes were all “in the middle” relative to the other two street segments.



Looking east on the north side of Alameda

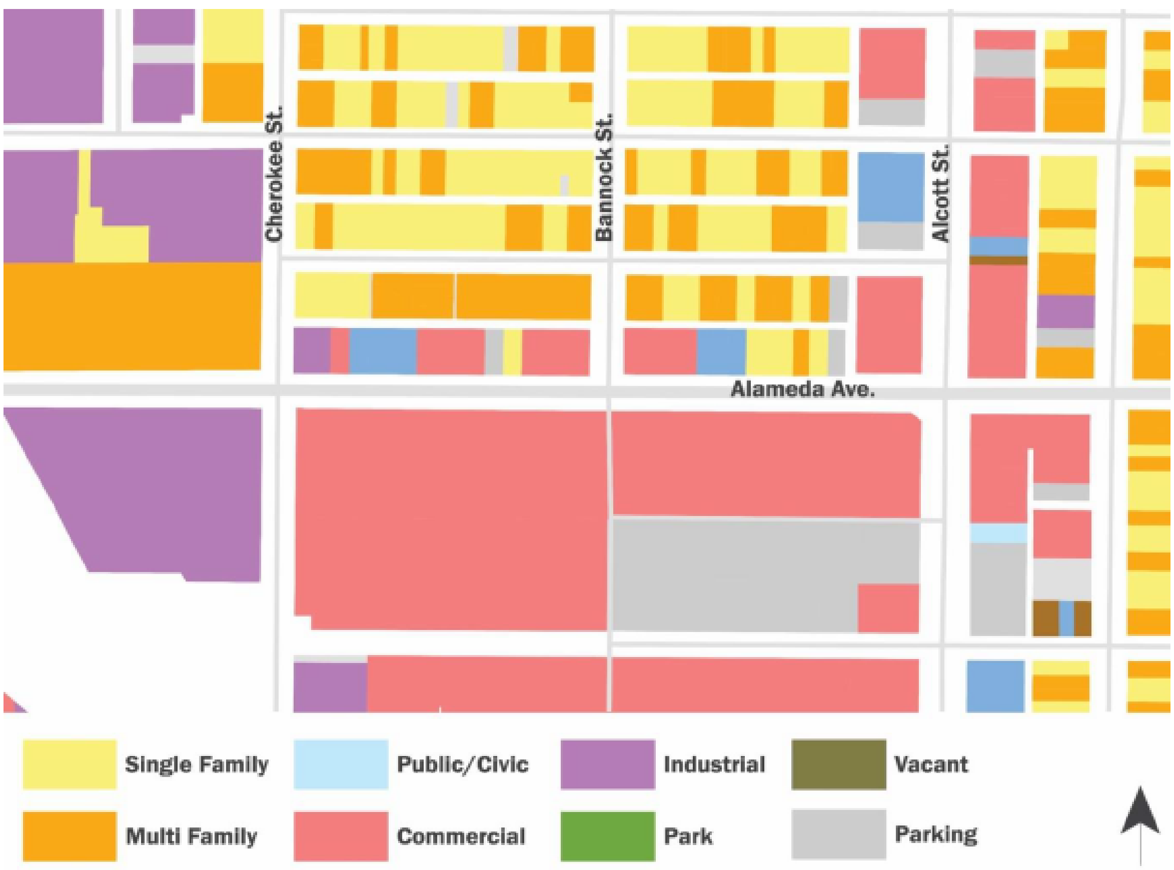


Looking west on the north side of Alameda

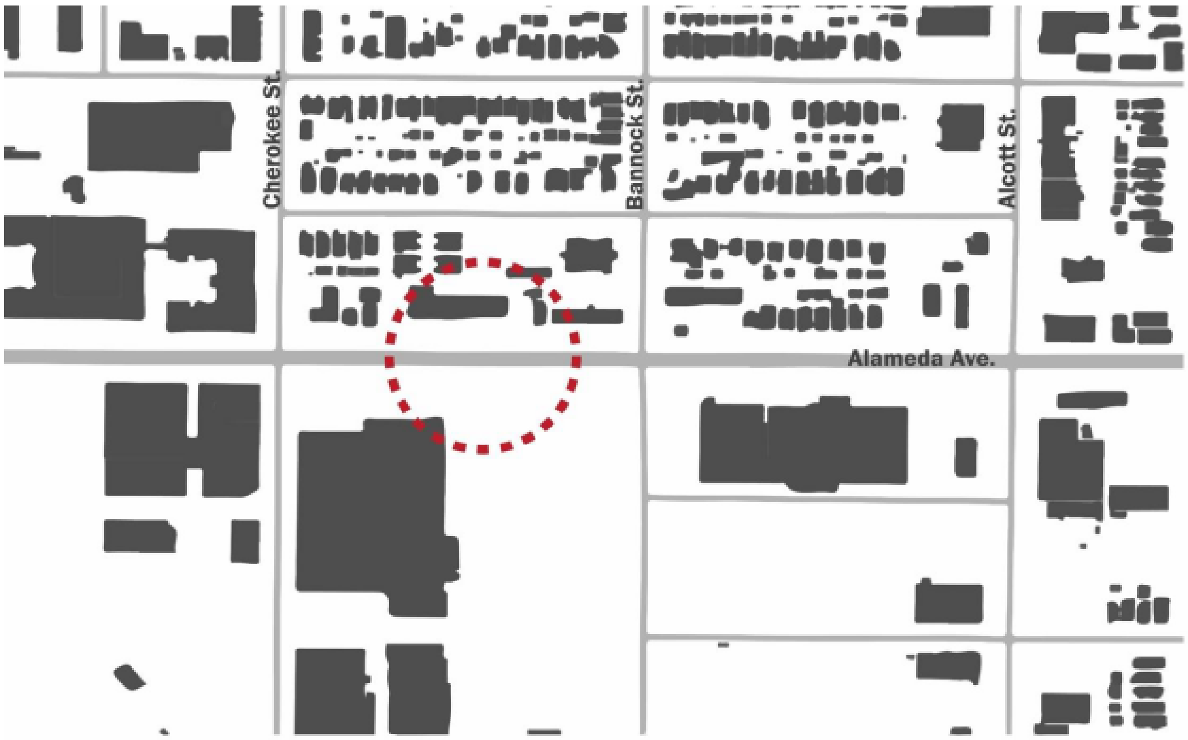
Land Use and Building Form Context

The second street segment was located along a primarily commercial, auto-oriented block of Alameda Ave. This block includes a K-Mart and its associated parking lot on the south side of Alameda and a variety of businesses and one single-family home on the north side of Alameda. Buildings are setback about 25 to 50 ft from the edge of the sidewalk on the north side of Alameda. Most building entrances orient toward Alameda Ave, thought the K-Mart does not. Higher-density, mixed use office and residential development near Alameda Station is located just one block to the east.

Land Use Map



Building Figure Ground



Neighborhood Characteristics

The neighborhood surrounding Street Segment 2 exhibits a couple of different street network typologies. To the north and east, it is generally a rectilinear grid form with long, narrow blocks. Typical block dimensions are about 300 feet (north-south) by 630 feet (east-west). To the west and south, the street network is still grid-like but the grid has been broken into much larger blocks and is sliced by railroad tracks, I-25, and the Platte River to the west.

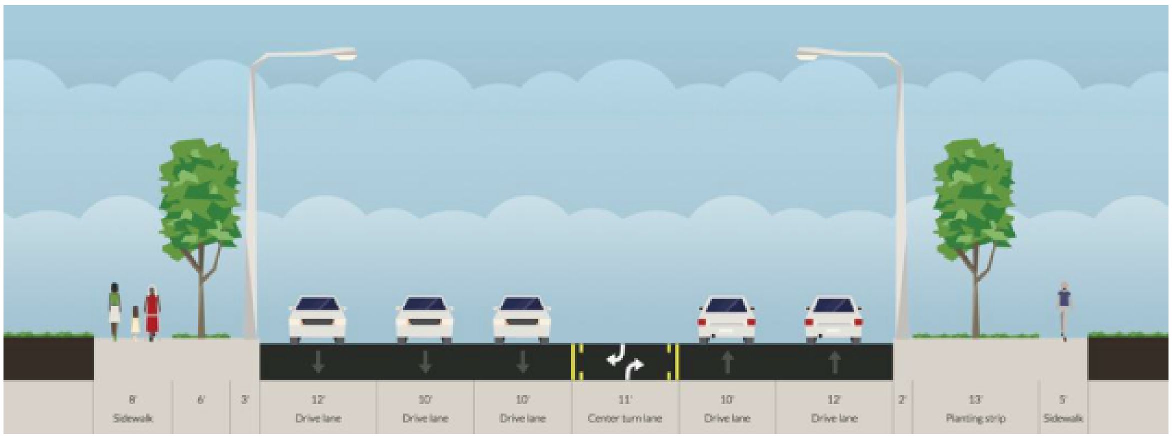
This section of Alameda lies entirely within a single Census Tract with boundaries that entirely correspond with the Baker Neighborhood's boundaries. Data from the 2014 American Community Survey 5-Year Estimates indicate that this neighborhood is generally lower-income with a similar median age and percentage of racial and ethnic minorities as the City & County of Denver as a whole. Single occupant vehicle mode share to work for this neighborhood is slightly lower than Denver as a whole.

Selected Data for Census Tracts Adjacent to Street Segment 2

	Baker Neighborhood	Denver
Median Age	34.2	34.0
Median Individual Income	$22,416	$30,709
Percent Ethnic or Racial Minorities	47.9%	47.1%
SOV Mode Share (To Work)	62.1%	69.7%

Street Design

The second street segment has lane widths ranging from 10 to 12 feet. Detached sidewalks are located on both sides of the street with tree lawns separating the sidewalks from the street. The overall right-of-way width is approx. 102 feet, and the curb-to-curb width is approx. 65 feet. A total of five driveway curb cuts (one for the K-Mart on the south side of the street and four on the north side) are spaced along the block and range from about 30 to 65 feet wide.



Alameda between Bannock St and Cherokee St, looking west

Tree Canopy/Street Trees

The street segment along Alameda between Bannock St. and Cherokee St. contains a number of small, recently planted trees in the public right of way. While there are a few larger 12 to 18 inch diameter trees along this segment of Alameda, the majority of trees are in their infancy with diameters between 3 and 6 inches. The street trees are evenly spaced and purposefully planted in three tree lawns that separate the sidewalk and the street. The tree canopy of the blocks immediately surrounding this segment is approximately 35%, which is higher than the average canopy across the city of Denver. The tree canopy along Alameda Ave., the adjacent sidewalks, and street front lots between Cherokee St. and Broadway, which includes the study segment, is 32%. This is significantly higher than the W. Alameda segment between Clay and Canosa, which has a block canopy of 20.5% and segment canopy of 0%.

Tree Canopy Map: Alameda and Bannock

Canopy within surrounding blocks: 20.5%

Canopy along Alameda and adjacent frontage lawns and sidewalks: 0%

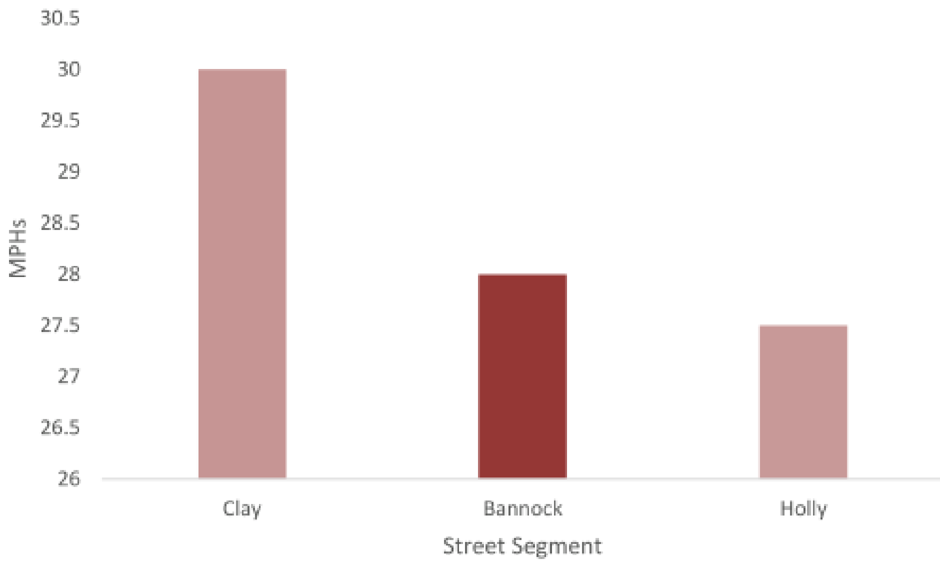
<u>Traffic Count</u>

The number of vehicles were counted over a period of ten minutes on a Sunday afternoon between 3:00 pm and 4:00 pm. 158 westbound cars passed the data collection location (about 320 feet to the west of the intersection of Alameda and Bannock) which would equate to approximately 22,752 cars per 24 hours. According to recent DRCOG traffic counts, the Alameda and Bannock intersection sees approximately 31,111 cars per 24 hour period. During the period of measurement, there was one bike (riding eastbound on the sidewalk) and three pedestrians.

<u>Vehicular Speeds</u>

Vehicular speeds were measured over a period of ten minutes approximately 320 feet west of the Bannock and Alameda stop light. Measurements occurred on a Sunday afternoon between 3:00 pm and 4:00 pm to limit the potential confounding variables, such as congestion, that impact vehicular speed. The median speed of cars along the Bannock and Cherokee segment was 28.00 mph with a standard deviation of 5.04. During the period of review, the highest recorded speed was 46 mph and the lowest was 14 mph. The posted speed limit along this segment is 35 mph. Of the three recorded street segments, this segment had the largest range of speeds and a median speed of 2 mph less than the median speed between Clay and Canosa.

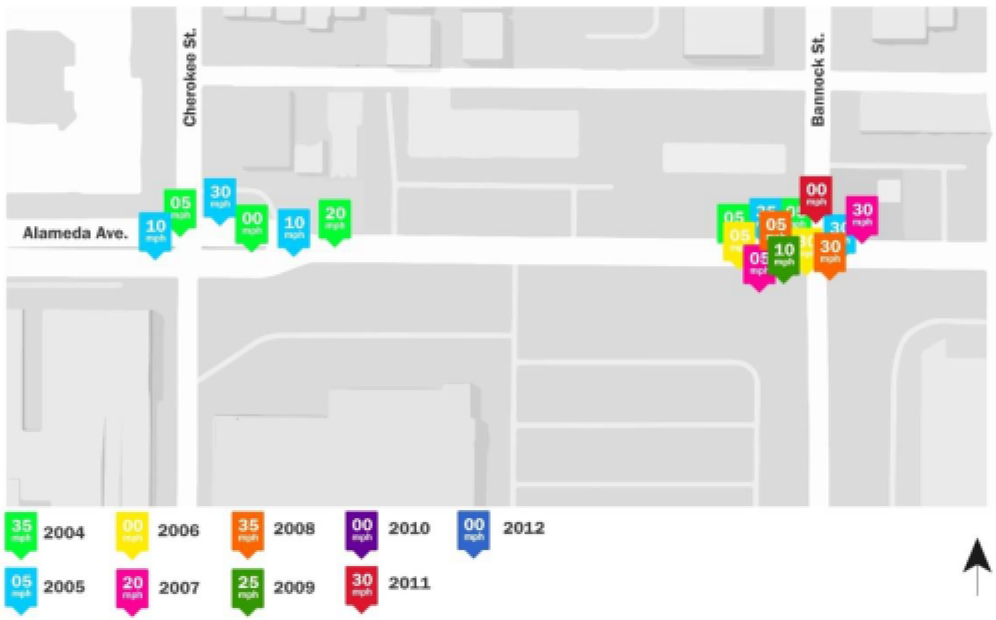
Vehicular Speed: Alameda and Bannock



<u>Traffic Accidents</u>

According to the DRCOG accident data between 2004 and 2012, this street segment experienced 18 accidents, approximately 2 accidents per year, with registered vehicle speeds ranging from 5 mph to 35 mph. There were no registered fatalities during this 9 year period. If around 31,000 cars pass along this street segment per 24 hour period, which equates to approximately 11,3000,000 cars per year, then this segment, with an average of 2 crashes per year has an accident risk of .0177 per 100,000 person years. The relative risk of the Bannock segment compared to the Clay segment is .437, which is less than 1, meaning the risk of driving on Alameda between Bannock and Cherokee is less than the segment between Clay and Canosa. The relative risk of the Bannock segment compared to Holly segment is 1.121, which is greater than 1, meaning the risk of driving on Alameda between Bannock and Cherokee is slightly greater than between Holly and Ivy.

Traffic Accident Map: Alameda and Clay



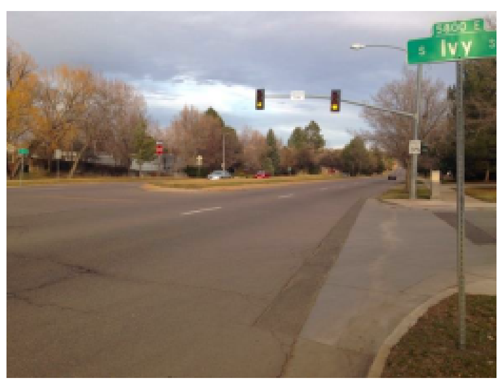
Total Accidents: 18

Accident Risk: .0177 per 100,000 person years

Street Segment 3: Alameda between Holly St and Ivy St (looking west)

The third street segment, which has larger street trees on both sides of Alameda Ave and within a median, is located in a residential area on the border of the Hilltop and Washington Virginia Vale Neighborhoods in Denver. The particular segment we chose has a relatively short block length of about 290 feet. Speed data and traffic counts were collected for eastbound traffic from a location approximately 240 feet to the east of the intersection of Alameda and Holly. Although this location had the widest lane widths, it had the lowest vehicle speeds and crashes, which supports the hypothesis that street trees improve safety outcomes.

Looking west on the south side of Alameda



Looking east on the south side of Alameda

Land Use and Building Form Context

The third street segment is located along a primarily residential section of Alameda Ave. Single family homes are located on both the north and south side of this block of Alameda, but only a few of them are oriented toward Alameda, and most include tall fences along the edge of the right-of-way. A fire station is located at the corner of Alameda and Ivy St.

Land Use Map

Building Figure Ground

Neighborhood Characteristics

The area surrounding Street Segment 3 generally has a rectilinear grid street network with long, narrow blocks. Typical block dimensions south of Alameda are about 300 feet (east-west) by 630 feet (north-south). To the north of Alameda, blocks also have east-west lengths of about 300 feet, but they have slightly shorter north-south lengths of about 600 feet.

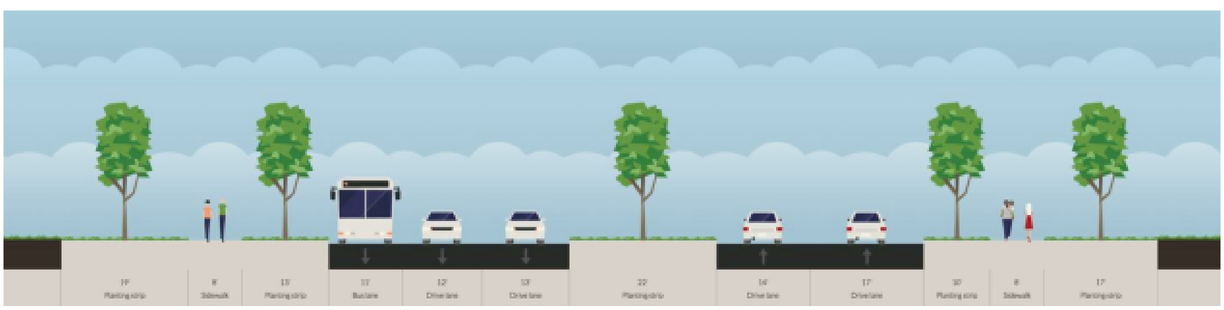
The two census tracts bordering this block of Alameda Ave cover the east half of the Hilltop neighborhood and the central part of the Washington Virginia Vale Neighborhood. Data from the 2014 American Community Survey 5-Year Estimates indicate that these census tracts have older, whiter populations than that of the City & County of Denver as a whole. The census tract within the Hilltop Neighborhood has higher individual incomes and a higher single occupant vehicle mode share than Denver as a whole, while the census tract within the Washington Virginia Vale Neighborhood is very close to the Denver average for these statistics.

Selected Data for Census Tracts Adjacent to Street Segment 3

	Hilltop East	Central Washington Virginia Vale	Denver
Median Age	41.6	42.3	34.0
Median Individual Income	$47,712	$30,612	$30,709
Percent Ethnic or Racial Minorities	13.3%	33.8%	47.1%
SOV Mode Share (To Work)	82.3%	69.4%	69.7%

<u>Street Design</u>

The third street segment has lane widths ranging from 11 to 17 feet. Curving, detached sidewalks are located on both sides of the street with tree lawns separating the sidewalks from the street and an additional tree lawn between the sidewalk and the property line. The overall right-of-way width is approx. 164 feet, and the curb-to-curb width is approx. 89 feet, including a 22-feet-wide median. A total of two driveway curb cuts (one for a home on the south side of the street and one for a home on the north side) are located on this block and range from about 30 to 40 feet wide.

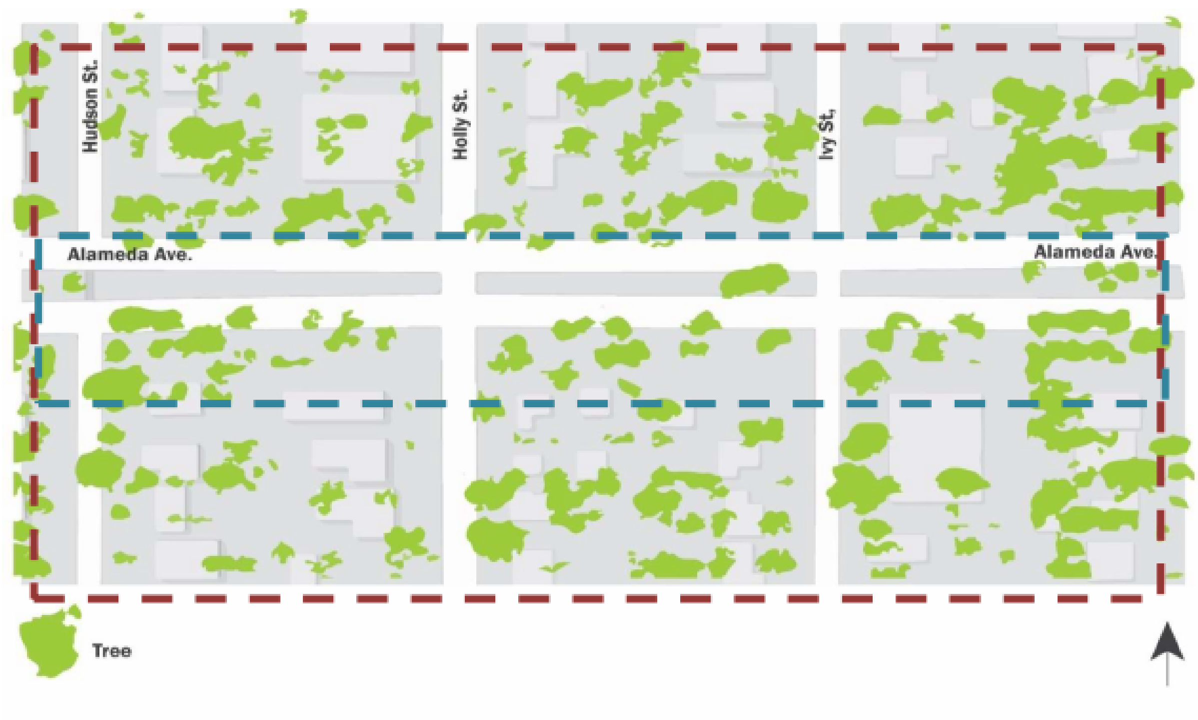


Alameda between Holly St and Ivy St, looking west

<u>Tree Canopy/Street Trees:</u>

The street segment along Alameda between Holly St. and Ivy St. contains a number of mature trees in the public right of way, including the tree lawns and dividing median. A mix between Ash and Locust, the trees are between 12 and 18 inches in diameter. It appears the street trees were evenly spaced in three tree lawns that separate the sidewalk and the street when originally planted. However as the trees have aged and property shifted ownership, some of the trees have been removed, leaving gaps in the consistent pattern. Unlike the Alameda segments to the west, this area is primarily dedicated to residential land use which allows for additional lawns and potential tree growth on the lots fronting the sidewalks. The tree canopy of the blocks immediately surrounding this segment is approximately 45%, which is higher than the average canopy across the city of Denver. The tree canopy along Alameda Ave., the adjacent sidewalks, and street front lots between Hudson St. and Jersey St., which includes the study segment, is 40%. This is significantly higher than both the W. Alameda segment between Clay and Canosa and central Alameda segment between Bannock and Cherokee.

Tree Canopy Map: Alameda and Holly



Canopy within surrounding blocks: 45%

Canopy along Alameda and adjacent frontage lawns and sidewalks: 40%

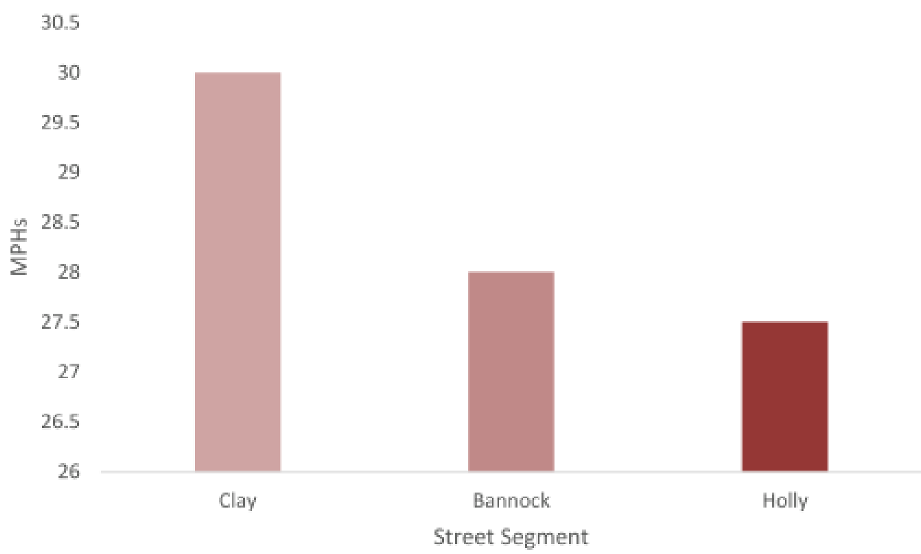
Traffic Count

The number of vehicles were counted over a period of ten minutes on a Sunday afternoon between 3:00 pm and 4:00 pm. 154 eastbound cars the data collection location (about 240 feet to the east of the intersection of Alameda and Holly) which would equate to approximately 22,176 cars per 24 hours. According to recent DRCOG traffic counts, the Alameda and Grape intersection, which is two blocks west, sees approximately 29,078 cars per 24 hour period. During the period of measurement, there were no bikes or pedestrians active on the sidewalk or in the road.

Vehicular Speeds

Vehicular speeds were measured over a period of ten minutes approximately 240 feet east of the Holly and Alameda stop light. Measurements occurred on a Sunday afternoon between 3:00 pm and 4:00 pm to limit the potential confounding variables, such as congestion, that impact vehicular speed. The median speed of cars along the Holly and Ivy segment was 27.50 mph with a standard deviation of 5.16. During the period of review, the highest recorded speed was 45 mph and the lowest was 18 mph. The speed limit along this segment is 35 mph. Of the three recorded street segments, this segment had the lowest median speed, approximately 2.5 mph lower than the median recorded between Clay and Canosa.

Vehicular Speed: Alameda and Holly



Traffic Accidents

According to the DRCOG accident data between 2004 and 2012, this street segment experienced 15 accidents, approximately 1.67 accidents per year, with registered vehicle speeds ranging from 5 mph to 35 mph. There were no registered fatalities during this 9 year period. If around 29,078 cars pass along this street segment per 24 hour period, which equates to approximately 10,600,000 cars per year, then this segment, with an average of 1.67 crashes per year has an accident risk of .0157 per 100,000 person years. The relative risk of the Holly segment compared to the Clay segment is .386, which is less than 1, meaning the risk of driving on Alameda between Holly and Ivy is less than between Clay and Canosa. The relative risk of the Holly segment compared to Bannock segment is .898, which is less than 1, meaning the risk of driving on Alameda between Holly and Ivy is slightly less than the segment between Bannock and Cherokee.

Traffic Accident Map: Alameda and Holly

Total Accidents: 15

Accident Risk: .0157 per 100,000 person years

Conclusion

This case study examined three street segments along Alameda Avenue, a major east-west arterial in Denver, in order to better understand the impact of street trees on safety. Despite arguments from traffic engineers and FWHA that street trees are hazardous objects that should be placed far from the roadway, our findings indicate that more and larger street trees and higher tree canopy coverage correlate with lower vehicle speeds, lower annual crashes, and lower relative crash risk. This was the case despite the fact that the street segments with trees had wider lane widths (which encourage higher speeds and riskier driving) than the street segment without trees.

Although this case study only examined three data points in areas with some differences in land use, demographic, socio-economic, and street design characteristics, the findings contribute to a growing body of research showing the benefits of street trees, particularly with regard to road safety. The implications of this case study and others like it for street design are clear: attempts to improve street safety by removing street trees are very likely misguided. Imposition of clear zone and sight distance guidelines on urban streets may encourage higher speeds and riskier driving behavior, causing an increase in crash risk. Thus, rather than removing street trees, our findings suggest that jurisdictions should plant *more* in order to make streets safer and to realize the many other benefits that street trees provide.

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Crash data: gis.drcog.org/datacatalog

Traffic count data: gis.drcog.org/trafficcounts

15. GIS METHODS AND ANALYSIS

Introduction

According to the National Highway Traffic Safety Administration (NHTSA) the United Stated has seen a 7.2% increase in traffic fatalities from 2014 to 2015 which is the largest increase seen in 5-decades (Henry, 2016). This increase is relevant almost across the board in SUV, Van, Passenger car, and pickup truck, motorcyclist, pedestrian, pedalcyclist, alcohol-impaired fatalities (USDOT, 2016). Denver County has also seen a steady increase in crash fatalities yearly from 33 in 2011 to 51 in 2015 (USDOT, Traffic Safety Facts Denver County); in addition, overall traffic crashes have increased from 15,655 in 2012 to 16,928 in 2015 (City and County of Denver, Crash Dashboard).

According to the National Association of City Transportation Officials (NACTO) Urban Street Design Guide, vehicle speed is a critical element in "cause and severity of crashes" and street trees are considered a speed reduction mechanism (NACTO, pgs. 140 and 142). The implication behind this statement is that street trees can be used as a mitigation element in roadway design to assist in increasing traffic safety; in addition, NACTO indicates that trees contribute to ecosystem health of a city and increase the aesthetic appeal (NACTO, pgs. 5 and 43).

The purpose of this paper is to determine what correlation(s) may exist between tree canopy coverage and traffic safety at street intersections and corridors. More specifically, the tree canopy coverage will be analyzed with crash rates, vehicle speeds, total number of crashes and crash severity.

With the use of geographic information systems (GIS) software, tree canopy spatial data will be evaluated with 10 sets of previously grouped streets that include segment types: light, moderate, heavy, and arterial. These grouped streets and their annual average daily traffic (AADT) counts have been previously obtained or field collected for all of these streets by Dr. Wesley Marshall at the University of Colorado Denver. Permission has been obtained by Dr. Marshall to use this data in this project. Please see Appendix A for a complete table of streets and an overview map detailing the areas for each group.

The defining characteristics for where each street segment under evaluation begins and ends will be based on 4 characteristics: Speed Limit, Operation (One-way or Two-way), Primary Surface Width, and Median (Present or Absent). The point of origin where these four characteristics are determined for each street will be based on the location where vehicle speed data was collected. Due to lack of free flow vehicle traffic, speed data collected at 3 locations have been removed from this project: Irvington, Colorado Blvd, and Inca (please Appendix A table).

The street segment area will be determined with the use of DRCOG Planimetrics – Edge of Pavement Polygons. This data provides the edge of paved and unpaved roadways in the Denver area, which enables for a more accurate representation of the primary surface of all road segments being evaluated.

Additional data that has been obtained to assist in the traffic safety analysis are car speeds recorded at all locations in the table above when leaves were present on trees (leaf on) and when leaves were absent on trees (leaf off).

Literature Review

Harvey et al. produced a research paper discussing the *perceived* effects of road safety in New York City which included tree canopy spatial data. This paper utilized GIS and subjective safety scores from the public. The tree canopy spatial data incorporated into the report was obtained from the University of Vermont with 1m resolution imagery and roadway width was based on the measurement of building edge to building edge as opposed to the "conventional curb-to-curb" method (Harvey, pgs.21-22). Advances in technologies such as aerial imagery today offer greater accuracy of public spatial data made available; therefore, affording the opportunity to achieve more accurate research and analysis with geospatial software. The City and County of Denver currently provide imagery at 2ft resolution and the Denver Regional Council of Governments (DRCOG) provides data extracted from imagery with a .5ft ground sampling distance.

Ewing and Dumbaugh discuss perception of safety and design features such as street trees but indicate that further research is needed. The final statement in their conclusion is a lack of understanding regarding influences design features have on vehicle speeds and crashes and a need for a better understanding "between design and crash incidence" (Ewing, pg. 364). The purpose of this paper is to delve directly into this need of further research and validation that street trees can indeed be a safety enhancement option.

Erdogan et al focuses on a study in Turkey where the first obstacle to overcome is converting text based crash information into spatial data and utilizing this to analyze crash locations. The extent of the analysis reviewed time of year and conditions to reveal trends but tree canopy was not used and there is little detail in the data pertaining to surface area coverage of the roadway (Erdogan, pg. 179). Data available for the City of Denver provide through DRCOG provides spatial data based on crash forms derived from State of Colorado Accident Reports for multiple years. This is a considerable advantage for time and resources by having this information readily available.

Denver offers advanced and viable data for research on road safety in the urban environment to go beyond the scope and results of previous research. This project will utilize GIS technologies to delve further into the detail for determining quantitative information regarding the correlation between street trees and road safety.

Data Details

Overview

The primary goal of this paper is to obtain and analyze spatial data to review the effect of tree canopy coverage of select roadways in Denver relevant to traffic safety and crash data. The spatial data necessary to achieve this analysis is road corridor and intersection primary surface area. The attributes pertaining to the corridors and intersections needed for analysis in addition to the named roads previously determined are the following: annual average daily traffic (AADT), primary surface width, speed limit, median (present or absent), and operation (one-way or two-way). All AADT has been obtained from prior research with the permission of Dr. Wesley Marshall at the University of Colorado Denver Civil Engineering Department.

Additional spatial datasets and tables were obtained from 3 sources: The University of Colorado Denver, Colorado Department of Transportation (CDOT), Denver Regional Council of Governments (DRCOG), and the City and County of Denver.

Colorado Department of Transportation (CDOT)

CDOT provides county level spatial data for Denver which includes highways, major roads, and local roads. All of this data is provided in a polyline format through the CDOT Online Transportation Information System (OTIS). CDOT also provides an Inventory Road Information System (IRIS) Microsoft Access Database which contains the Transportation Colorado Roadway Information System (TCORIS) for Colorado highways. IRIS is produced annually and provides information pertaining to Colorado highways.

Highways

The CDOT highway spatial data consists of interstate, state highways, and US highways under CDOT jurisdiction in a polyline geospatial data format. This spatial data does not contain all of the necessary attributes, most notably primary surface width, to determine segmentation for analysis; therefore, the spatial data is created using the TCORIS table. The process for creation of this spatial data will be discussed in further detail in the "Methods" section of this paper.

The fields in the highway and TCORIS data used for the creation of primary surface width are listed below and described in detail in Appendix B.

Field Name	Brief Description	Description	Comments
PriThruLnQty	Thru Lane Quantity (Primary Direction of Traffic)	Appendix B	Appendix B
PriThruLnWd	Thru Lane Width (Primary Direction of Traffic)	Appendix B	Not Available
SecThruLnQty	Thru Lane Quantity (Secondary Direction of Traffic)	Appendix B	Appendix B
SecThruLnWd	Thru Lane Width (Secondary Direction of Traffic)	Appendix B	Appendix B
PriLTurnWd	Left Turn Lane Width (Primary Direction of Traffic)	Appendix B	Appendix B
PriLTurnQty	Left Turn Lane Quantity (Primary Direction of Traffic)	Appendix B	Appendix B
SecLTurnWd	Left Turn Lane Width (Secondary Direction of Traffic)	Appendix B	Appendix B
SecLTurnQty	Left Turn Lane Quantity (Secondary Direction of Traffic)	Appendix B	Appendix B
PriAuxLnWd	Primary Auxiliary Lane Width (Primary Direction of Traffic)	Appendix B	Appendix B
PriAuxLnQty	Primary Auxiliary Lane Quantity (Primary Direction of Traffic)	Appendix B	Appendix B
SecAuxLnWd	Auxiliary Lane Width (Secondary Direction of Traffic)	Appendix B	Appendix B
SecAuxLnQty	Auxiliary Lane Quantity (Secondary Direction of Traffic)	Appendix B	Appendix B
PriOutShldWd	Primary Outside Shoulder Width (Primary Direction of Traffic)	Appendix B	Not Available
SecOutShldWd	Outside Shoulder Width (Secondary Direction of Traffic)	Appendix B	Not Available
PriInShldWd	Left Inside Shoulder Width (Primary Direction of Traffic)	Appendix B	Not Available
SecInShldWd	Left Inside Shoulder Width (Secondary Direction of Traffic)	Appendix B	Appendix B
MedianWd	Median Width	Appendix B	Appendix B

Major Roads and Local Roads

The CDOT major roads spatial data "represent public roads under local jurisdiction that are functionally classified as arterials or collectors. Features are represented by polyline (linear) geographic shapes" (Major_Roads metadata, Description). Local roads spatial data "represent public roads under local jurisdiction that are functionally classified as local. Features are represented by polyline (linear) geographic shapes" (Local_Roads metadata, Description).

The fields utilized in the major roads and local roads data are listed below and described in detail in Appendix C.

Field Name	Brief Description	Description	Comments
OPERATION	One-way or two-way operation	Appendix C	Appendix C
MEDIAN	Median Type	Appendix C	Appendix C
PRISURFWD	Primary Surface Width	Appendix C	Appendix C

Denver Regional Council of Governments (DRCOG)

Crash

DRCOG Crash Data Points from 2010-2013 were used for this report. The metadata description provided by DRCOG is the following: "This file contains a record for each reported traffic crash in the Region. The crash record provides information on the date, time, collision type, vehicle type, driver demographics, and contributing factors for each crash. The data originates from State of Colorado Traffic Accident Report Forms" (DRCOG Crash Data Points 2010, Description).

The fields from the crash spatial data in 2010-2013 that were used in the analysis consist of the following:

Field Name	Brief Description	Domain Entries	Description
ROAD	Road Description	01	At Intersection
		02	Driveway Access Related
		03	Intersection Related
		04	Non-Intersection
		05	Alley Related
		06	Roundabout
		07	Highway Interchange
		08	Parking Lot
INJLEVEL_0	Injury Severity		No Injury
INJLEVEL_1	Injury Severity		Complaint of Injury
INJLEVEL_2	Injury Severity		Evident – non-incapacitating
INJLEVEL_3	Injury Severity		Evident - incapacitating
INJLEVEL_4	Injury Severity		Fatal

Planimetrics

DRCOG Planimetrics – Edge of Pavement Polygons is part of a project undertaken in 2015 utilizing aerial imagery obtained to create infrastructure spatial data (ESRI, ArcUser, pg.20). This data provides the edge of paved and unpaved roadways in the Denver area, which enables for a more accurate representation of the primary surface of all roadways being evaluated. The metadata description for additional detail is as follows: *"This metadata describes the stereocompiled Edge of Pavement (EOP) polygons feature of DRCOG Denver Region Urbanized Project Area. The feature was compiled from the Denver Regional Aerial Photography Project (DRAPP) 2014 Aerial Imagery Acquisition and Production. This 1"=100' scale imagery is comprised of 4-band RGBIR color orthoimagery with a GSD (Ground Sample Distance) of 0.5'. Imagery was collected with the Leica ADS40 and ADS80 digital sensors and processed with Leica XPro software. Imagery is projected in State Plane Coordinate System, Colorado central zone using the Lambert Conformal Conic map projection parameters. Horizontal and vertical datums are NAD83(11) and NAVD88(GEOID12A) respectively"* (PLANIMETRICS_2014_EDGE_PAVEMENT_POLYGON_TOTAL, Metadata, Description).

The City and County of Denver

Tree Canopy

The tree canopy data provided by the City and County of Denver is from 2006 "QuickBird 2 foot pixel satellite imagery, using automated feature extraction from the near infra-red band" (City and County of Denver Open Data Catalog, abstract).

Street Centerline

The street centerline spatial dataset provides information pertaining to the City and County of Denver streets. The attributes utilized in this report are the following:

Field Name	Description
FULLNAME	Prefix + name + type (+ suffix). Parkways also include the word 'STREET' or 'AVENUE' in the FULLNAME but are not found in the NAME. Considered these anomalies when concatenating.
SPEEDLIMIT	The speed limit of the street segment.
ONEWAY	Identifies a roadway as a one-way or two-way operation. 1 = direction of increasing address range; 2 = travel in direction of decreasing address range, 0 = two way travel on the street segment.
MEDIAN	Median exists = Yes, No, or Circle Median.

University of Colorado Denver

AADT

The annual average daily traffic (AADT) information was obtained from prior research conducted by Dr. Wesley Marshall in the University Of Colorado Denver Department Of Civil Engineering and included in this report with his permission.

Speed Data

Protocol and roads that were focused on for this report were obtained with permission from Dr. Wesley Marshall from the University of Colorado Denver. The arterial for each "SITEID" group has been provided with 2 cross streets as the segment of interest. The aim for speed data collection locations for the heavy, moderate, and light street locations was based on approximately a one or two block vicinity of the arterial road location. Based on access, visibility, and location to observe and collect data, this location at times needed to be moved further away.

The protocol provided referred to research performed by the "Connecticut Transportation Institute of the University of Connecticut" and documented in "Designing Roads That Guide Drivers to Choose Safer Speeds." This included only collecting data from passenger cars, minivans, and light trucks and speed data collection was conducted either in a parked car, seated behind an obstruction from the drivers view, or out front a residence with permission from the landowner (Ivan, pg.11). Weather conditions for all data collected was clear and dry (Ivan, pg.11). Vehicles were observed before recording their speed to ensure they were not inhibited by traffic patterns such as heavy traffic, speeding up after making a turn, slowing down to make a turn, slowing to park, or any other constraints disabling the driver from moving at a free flow speed (Ivan, pg.11).

Speed data was collected during 2 different times of the year when leaves were off of the trees (January to April 2016) and when leaves were on the trees (June to July 2016) at the same locations.

Please see Appendix D for a complete table of all speed data collected and AADT for roads in this report.

Methods

Spatial Data Preparation

Street Segment Characteristics

The 4 characteristics to determine the beginning and end of each street segment are the following: Speed Limit, Operation (One-way or Two-way), Primary Surface Width, and Median (Present or Absent). Each highway, major road, and local road characteristics were identified where speed data was collected in the field. Once the 4 characteristics were identified at the location of speed data collection, the beginning and end of the segment was determined wherever any of these characteristics changed.

The preparation of the highway, major road, and local road data to determine these characteristics was different and it is explained in further detail below.

Highways

CDOT provides a polyline geospatial dataset for highways in Denver County, which includes the number of travel lanes, travel lane width, and median width. These measurements enable a primary surface width to be calculated with the following formula (travel lanes * travel lane width) + median width. These results were compared to CDOT's Online Transportation Information System (OTIS) Highway Explorer, which provides the ability to search for highway attribute attributes online.

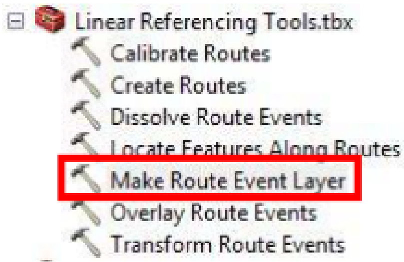
The primary surface width was compared between the calculations in the CDOT highway GIS data to the OTIS Highway Data Explorer in 10 locations. None of the results matched indicating the need to contact CDOT for more accurate data and an explanation. Please see Appendix E for the complete table of results.

Based on conversation with GIS Analyst Ted Howard at CDOT, there is a table for highways maintained by CDOT titled TCORIS mentioned earlier in the report. This attribute information provided an accurate assessment of surface widths that could be used to calculate primary surface area, which leads to step 1 of the data creation process below.

Step 1 Dynamic Segmentation

CDOT GIS Analyst Ted Howard provided an explanation on how to create a spatial dataset from the TCORIS table utilizing a process called "dynamic segmentation." Mr. Howard provided a finalized dataset and also explained the process to create this, which enabled me to recreate the data and mimic the steps for future use.

"Dynamic segmentation (DynSeg) is the process of computing the map location (shape) of events stored in an event table. Dynamic segmentation is what allows multiple sets of attributes to be associated with any portion of a linear feature" (ArcGIS 10.3 help, dynamic segmentation process). This geospatial process is initiated by importing the highways polyline spatial data and the TCORIS table into a file geodatabase. Using the "Make Route Event Layer" toolbox activates this process and updates the highways spatial data to include the TCORIS attributes.



Step 2 Calculate primary surface width

A new field was created in the highway geospatial data and the following VB Script was entered to calculate the primary surface width:

(Pri lane width * Pri thru lane quantity) + (Sec lane width * Sec thru lane quantity) + (Pri or Sec Turn Lane width * Pri or Sec Turn Lane quantity) + (Pri 0r Sec Aux Lane width * Pri or Sec Aux Lane quantity) + (Pri Outside Shoulder width) + (Sec Outside Shoulder width) + (Pri Inside Shoulder width) + (Sec Inside Shoulder width)

Step 3 Calculate Median

Median field entries in the TCORIS attributes were simplified from the original entries to a newly calculated field stating “Y” for median present and “N” for median absent.

Median (TCORIS)	Calculated Field
1 None	N
12 Painted - No Vehicles	Y
13 Parking	
14 Level	
21 Depressed	
31 Raised (no curb)	
41 Raised Curb	
52 Channelized - Raised Curb	
54 Channelized - Painted	
55 HOV Reversible	

Step 4 Dissolve

5 fields were used for dissolving the CDOT highway data: route, speed limit, median (present or absent), operation (one-way or two-way) and primary surface width.

Major and Local Road

Step 1 Compare CDOT Major and Local Road Data and The City and County of Denver Data

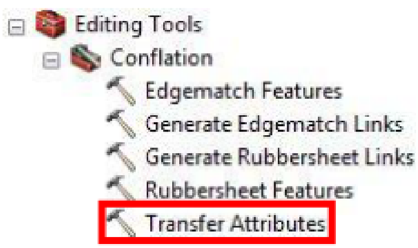
Utilizing CDOT as the sole source for all roads data would have been optimal when conducting analyses for this project; however, upon review of CDOT and the City and County of Denver roads data for local and major roads, there were differences in attributes between the two. For example, the field “Primary Surface Width” is provided for *some* of the CDOT major and local roads but this field is not available in the City and County of Denver’s data.

CDOT was contacted to further investigate the source of the data they provide and validate the accuracy. The response consisted of verification that CDOT is not the *originator* of this data; however, they receive all data from the City and County of Denver every year per highway users' tax fund (HUTF) standards (Howard, Email Correspondence). Please see Appendix F for the original email. The HUTF is obtained through fuel taxes, traffic fines, and motor vehicle charges and fees which is then divided among the cities, counties and the state (CDOT) (CDOT, State Funding Sources).

Further inquiries were made with staff at CDOT to determine why there were differences in the data. Aaron Rhodes is a Data Management Local Roads Specialist with CDOT and was only able to verify that all spatial data is received directly from the City and County of Denver but he was unable to provide any further information pertaining to missing attribute entries or additional attributes in the CDOT data (Rhodes, Email Correspondence). Please see Appendix F for the original email. Inquiries with the City and County of Denver did not receive any reply.

Step 2 Combine CDOT and the City and County of Denver Road Data

To obtain attribute entries for all streets, both CDOT and City and County of Denver spatial data were used. In order to accomplish utilizing attributes from 2 different linear spatial data sets (CDOT and the City and County of Denver) that do not geospatially share the same vertices, the "Transfer Attributes" geospatial tool is used.



Based on manual review of attribute entries and spatial location of data from both sources, CDOT was determined to have greater accuracy and this linear spatial data was used as the primary in the "Transfer Attributes" geospatial tool. This data received the attributes from The City and County of Denver and was the exported final dataset upon completion of the geoprocess.

The "Tool Help" provides additional information stating roads data is an example where this is an appropriate use for its functionality. Please see an excerpt below taken from ArcGIS 10.3 Help describing this tool.

"Transfer Attributes"

Finds where the source line features spatially match the target line features and transfers specified attributes from source features to matched target features.

Attribute transfer is typically used to copy attributes from features in one dataset to corresponding features in another dataset. For example, it can be used to transfer the names of road features from a previously digitized and maintained dataset to features in a new dataset that are newly collected and more accurate. The two datasets are usually referred to as source features and target features. This tool finds corresponding source and target line features within the specified search distance and transfers the specified attributes from source lines to target lines." (ArcGIS 10.3 Help, Transfer Attributes (Editing))

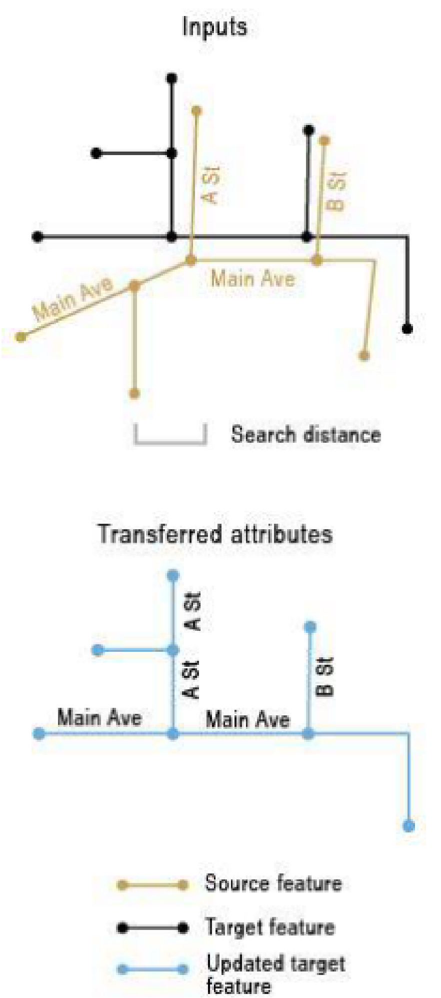


Image Source: ArcGIS 10.3 Help, Transfer Attributes (Editing)

Step 3

Any roads that contained the CDOT primary surface width and median attributes were retained. Empty entries for primary surface width were calculated from The City and County of Denver data with the calculation of: lane width * number of lanes. Any empty attributes in the CDOT data were obtained from The City and County of Denver data.

Step 4 Dissolve

5 fields were used for dissolving the newly created roads data from the "Transfer Attributes" geoprocessing function: route name, speed limit, median (present or absent), operation (one-way or two-way) and primary surface width.

Determine Street Segment Start and End Point

The point of origin for determining characteristics that would define the extent of each street segment was the location where speed data was collected. Utilizing the attributes from the dissolved highways, major, and local roads which included road name and the 4 fields containing the characteristics desired, these datasets were used to extract the extent for each Site ID light, moderate, heavy and arterial road.

After selecting dissolved highway, major road, and local road spatial extents, these extents were manually reviewed. Spatial data often has errors or anomalies due to data entry or user error when performing spatial geoprocesses which requires quality assurance / quality control (QA/QC) checks for verification. This review resulted in an error noticed in the dissolve due to roadway names. For example, "N Broadway" will change names to "S Broadway" but the attributes did not change. Therefore, this necessitated a manual update in the data to extend the true extent of this road.

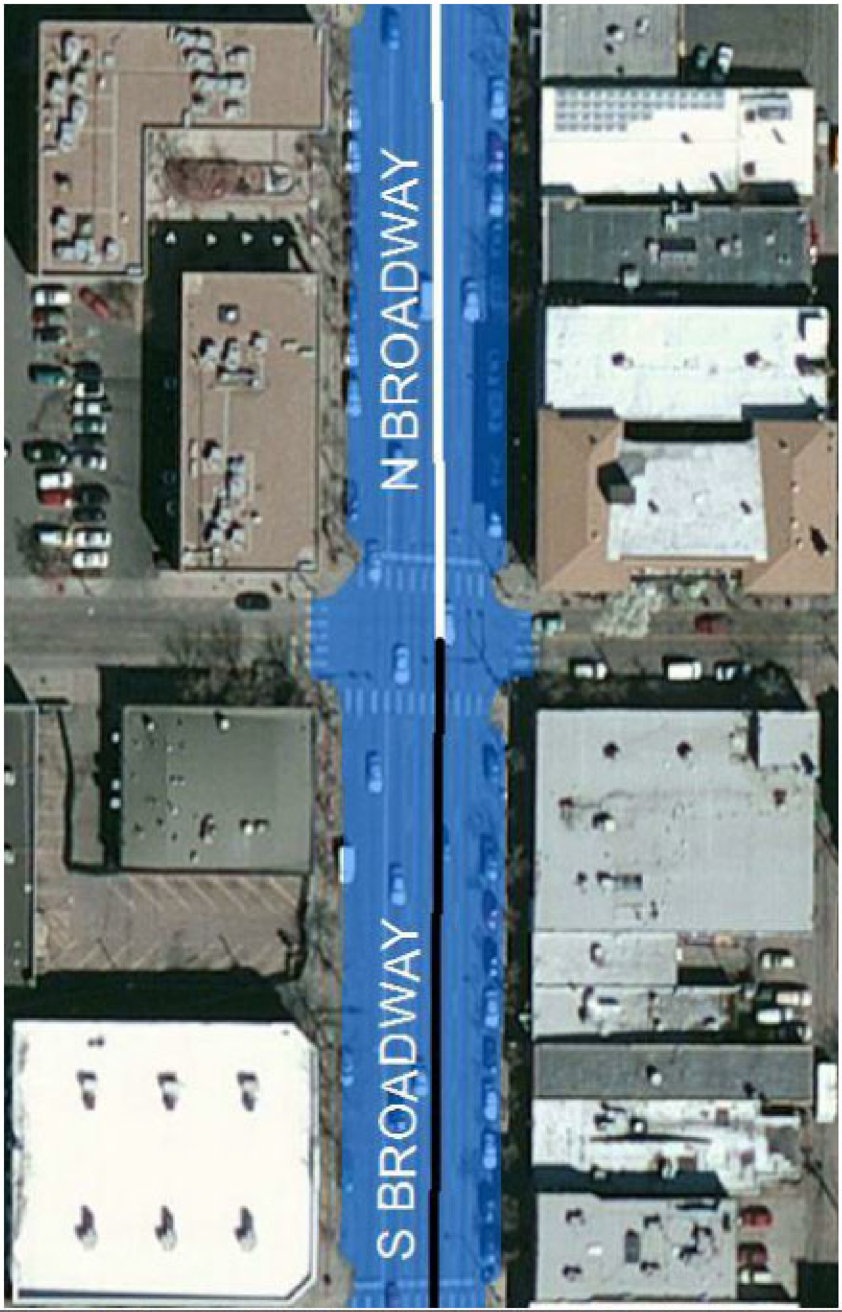
Some of the roads have slight changes in names even though the criteria remains the same. For instance, N Broadway and S Broadway may have the same speed limit, median presence, operation, and primary surface width but they would be separated in the GIS data because it is a different name.

Please see the example below:

Point of origin where speed data was collected
Site ID 14 | Arterial | Broadway

FULLNAME	SPEEDLIMIT	ONEWAY	MEDIAN	PRISURFWD
N BROADWAY	30	1	N	72

Two separate spatial features with the same characteristics
Spearated due to change in street name

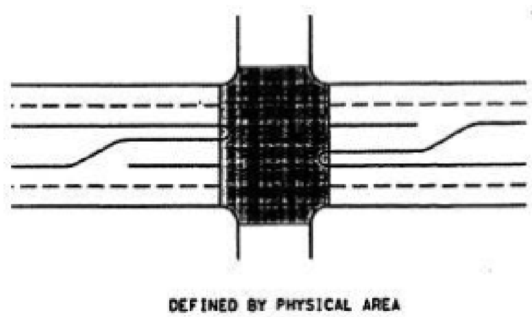


FULLNAME	SPEEDLIMIT	ONEWAY	MEDIAN	PRISURFWD
N BROADWAY	30	1	N	72
S BROADWAY	30	1	N	72

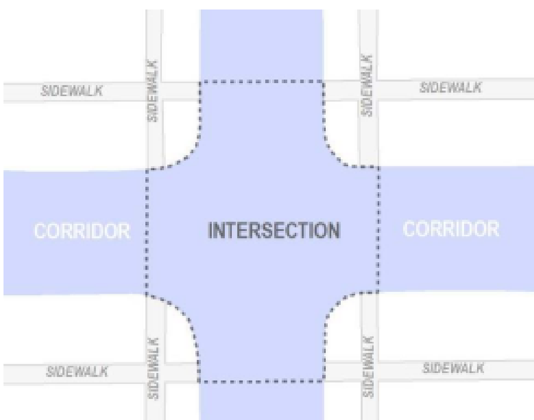
Creating Primary Surface Area

The AASHTO Green Book provides a visual depiction of an intersection that is defined by the physical area (please see image below). The corridor segmentation is defined in this paper by the primary surface width and the area of coverage through the planimetrics data obtained from the Denver Regional Council of Governments (DRCOG). The basis of spatial reference for roadway data and segmentation is focused on physical area and physical area characteristics; therefore, intersection will be spatially created and characterized in a similar method.

This area of coverage will be used to represent intersection primary surface areas; in addition, the areas between intersections will be used to represent corridor surface areas. Crosswalk planimetric data will be used to help determine the distinction of where the intersection ends and roadway begins and vice versa.



Source: AASHTO Green Book Page 557



Spatial Data Analysis

Calculating Primary Surface Width

Primary surface width is an attribute entry provided for all CDOT highways and only a portion of the major roads and local roads. Local and major road data is provided by the City and County of Denver; however, their spatial data does not provide a primary surface width attribute. Further investigation was conducted with Aaron Rhodes (Local roads specialist) at CDOT to determine how the primary surface width is calculated and why it is only provided for a portion of the local and major roads in their spatial data. Unfortunately, no answer or additional information was able to be provided.

Further evaluation of the local and major roads was conducted to determine if the primary surface width attribute provided by CDOT was more accurate than calculating a primary surface width using the City and County of Denver spatial data. The only 2 fields in the City and County of Denver that would allow for the creation of a primary surface width is "TRAVLANES" and "LANEWIDTH". Multiplying these two attribute entries would provide the only possible estimated calculation using the City and County of Denver data.

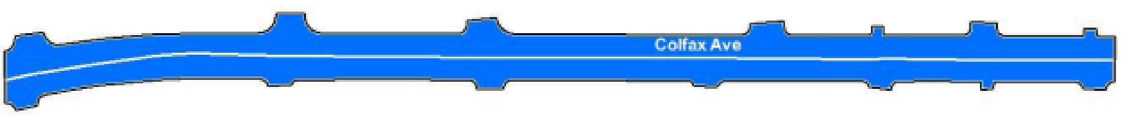
A comparison of the CDOT primary surface width was conducted with the City and County of Denver data. The results are as follows for 10 street segments:

Road	CDOT (Primary Surface Width)	City and County of Denver (Travel Lanes x Lane Width)	Planimetrics (Manual Measurement in GIS)
E 10th Ave	36ft	20ft (2 x 10)	34.75ft
E Mexico Ave	36ft	20ft (2 x 10)	36.0ft
Glencoe St	30ft	20ft (2 x 10)	30.7ft
N Fairfax St	30ft	20ft (2 x 10)	30.2ft
S Garfield St	36ft	20ft (2 x 10)	35.8ft
N Sherman St	36ft	20ft (2x 10)	35.6ft
N Santa Fe Dr	52ft	30ft (3 x 10)	34.7ft / 46.7ft
N Kalamath St	52ft	30ft (3 x 10)	49.9ft
N Galapago St	40ft	20ft (2 x 10)	41.1ft
E 14th Ave	36ft	30ft (3 x 10)	35.9ft

Based on the results showing above, the most accurate attribute entries are provided by CDOT. Any attribute entries not provided by CDOT were entered using the City and County Denver information.

Calculating Street Segment Length

Street segment lengths were created using the City and County of Denver street centerline geospatial data. Utilizing the primary surface area created for each segment, the roadway centerlines were clipped to the bounding area for each segment.



Calculating Tree Canopy Coverage

Tree canopy coverage was calculated using the City and County of Denver 2006 tree canopy spatial data.

SiteID	Type	StreetName	Cross_1	Cross_2	UCD_PriSur	PctCanopy
2	Arterial	University Blvd	Exposition	Ohio	Intersection	9.30%
2	Arterial	University Blvd	Exposition	Ohio	Road Segment	20.67%
2	Heavy	Exposition			Intersection	6.09%
2	Heavy	Exposition			Road Segment	15.92%
2	Light	Bonnie Brae			Intersection	10.25%
2	Light	Bonnie Brae			Road Segment	19.51%
2	Moderate	York			Intersection	11.61%
2	Moderate	York			Road Segment	39.87%
3	Arterial	23rd Avenue	Cherry	Dexter	Intersection	4.02%

3	Arterial	23rd Avenue	Cherry	Dexter	Road Segment	12.27%
3	Heavy	Montview			Intersection	23.81%
3	Heavy	Montview			Road Segment	17.31%
3	Light	Dexter			Intersection	16.92%
3	Light	Dexter			Road Segment	32.53%
3	Moderate	26th			Intersection	6.83%
3	Moderate	26th			Road Segment	8.80%
6	Arterial	Broadway	1st	Bayaud	Intersection	1.84%
6	Arterial	Broadway	1st	Bayaud	Road Segment	7.50%
6	Heavy	Lincoln			Intersection	1.49%
6	Heavy	Lincoln			Road Segment	5.78%
6	Moderate	1st			Intersection	3.49%
6	Moderate	1st			Road Segment	8.63%
7	Arterial	44th Avenue	Meade	King	Intersection	3.59%
7	Arterial	44th Avenue	Meade	King	Road Segment	4.41%
7	Heavy	Lowell			Intersection	9.11%
7	Heavy	Lowell			Road Segment	7.22%
7	Light	King			Intersection	19.51%
7	Light	King			Road Segment	28.39%
7	Moderate	Irving			Intersection	5.87%
7	Moderate	Irving			Road Segment	23.95%
11	Arterial	Holly Street	Ivanhoe	Gunnison	Intersection	0.09%
11	Arterial	Holly Street	Ivanhoe	Gunnison	Road Segment	4.79%
11	Heavy	Florida			Intersection	1.38%
11	Heavy	Florida			Road Segment	3.01%
11	Light	Hudson			Road Segment	4.37%
11	Moderate	Louisiana			Intersection	4.84%
11	Moderate	Louisiana			Road Segment	10.84%
12	Heavy	14th			Intersection	5.22%
12	Heavy	14th			Road Segment	15.75%
12	Light	Fairfax			Intersection	2.62%
12	Light	Fairfax			Road Segment	26.79%
12	Moderate	Glencoe			Intersection	6.49%
12	Moderate	Glencoe			Road Segment	29.42%
13	Heavy	Florida			Intersection	1.38%
13	Heavy	Florida			Road Segment	3.01%
13	Light	Garfield			Intersection	2.12%
13	Light	Garfield			Road Segment	4.60%
13	Moderate	Mexico			Intersection	0.72%
13	Moderate	Mexico			Road Segment	6.02%
14	Arterial	Broadway	8th	12th	Intersection	0.77%

14	Arterial	Broadway	8th	12th	Road Segment	1.63%
14	Heavy	11th			Intersection	5.32%
14	Heavy	11th			Road Segment	12.95%
14	Light	Sherman			Intersection	4.62%
14	Light	Sherman			Road Segment	16.84%
14	Moderate	10th			Intersection	6.53%
14	Moderate	10th			Road Segment	26.85%
15	Arterial	Santa Fe Dr	12th	7th	Intersection	0.09%
15	Arterial	Santa Fe Dr	12th	7th	Road Segment	0.99%
15	Heavy	Kalamath			Intersection	0.41%
15	Heavy	Kalamath			Road Segment	8.55%
15	Moderate	Galapago			Intersection	2.67%
15	Moderate	Galapago			Road Segment	7.24%
19	Arterial	Colfax Ave	York	Cook	Intersection	4.60%
19	Arterial	Colfax Ave	York	Cook	Road Segment	4.07%
19	Heavy	14th			Intersection	6.15%
19	Heavy	14th			Road Segment	11.31%
19	Light	Steele			Intersection	10.06%
19	Light	Steele			Road Segment	43.39%
19	Moderate	Fillmore			Intersection	9.12%
19	Moderate	Fillmore			Road Segment	38.50%

Calculate Average Number of Crashes per Year

The average number of crashes per year was determined for 2010 -2013 using the DRCOG crash data and the corridor and intersection for each road segment. The DRCOG crash data contains a field titled "ROAD" which is the "Road Description" from block D on the "State of Colorado Traffic Accident Report." Block D on this report provides the following entries:

D. ROAD DESCRIPTION

01. At Intersection
02. Driveway Access Related
03. Intersection Related
04. Non-Intersection
05. Alley Related
06. Roundabout
07. Highway Interchange
08. Parking Lot

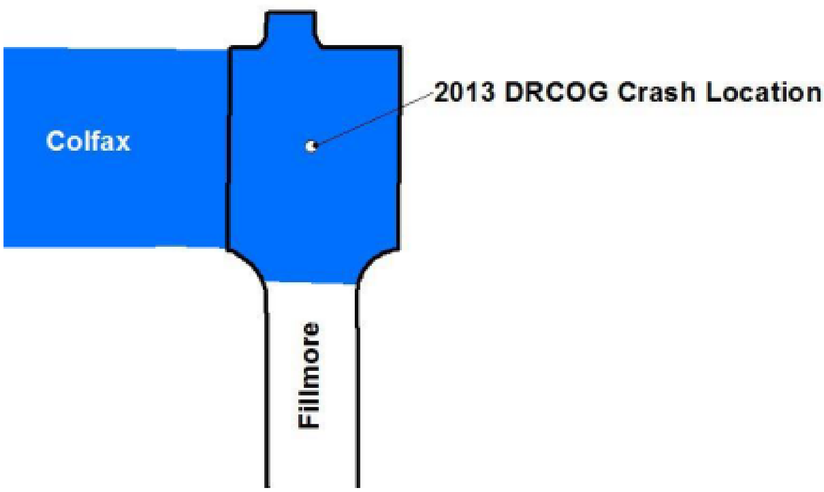
This field was used to determine which accidents occurred in the corridor and the intersection in the following manner:

Field Name	Value	Definition	Query
Road	01	At Intersection	Intersection
	02	Driveway Access Related	Corridor
	03	Intersection Related	Intersection
	04	Non-Intersection	Corridor
	05	Alley Related	Not Used

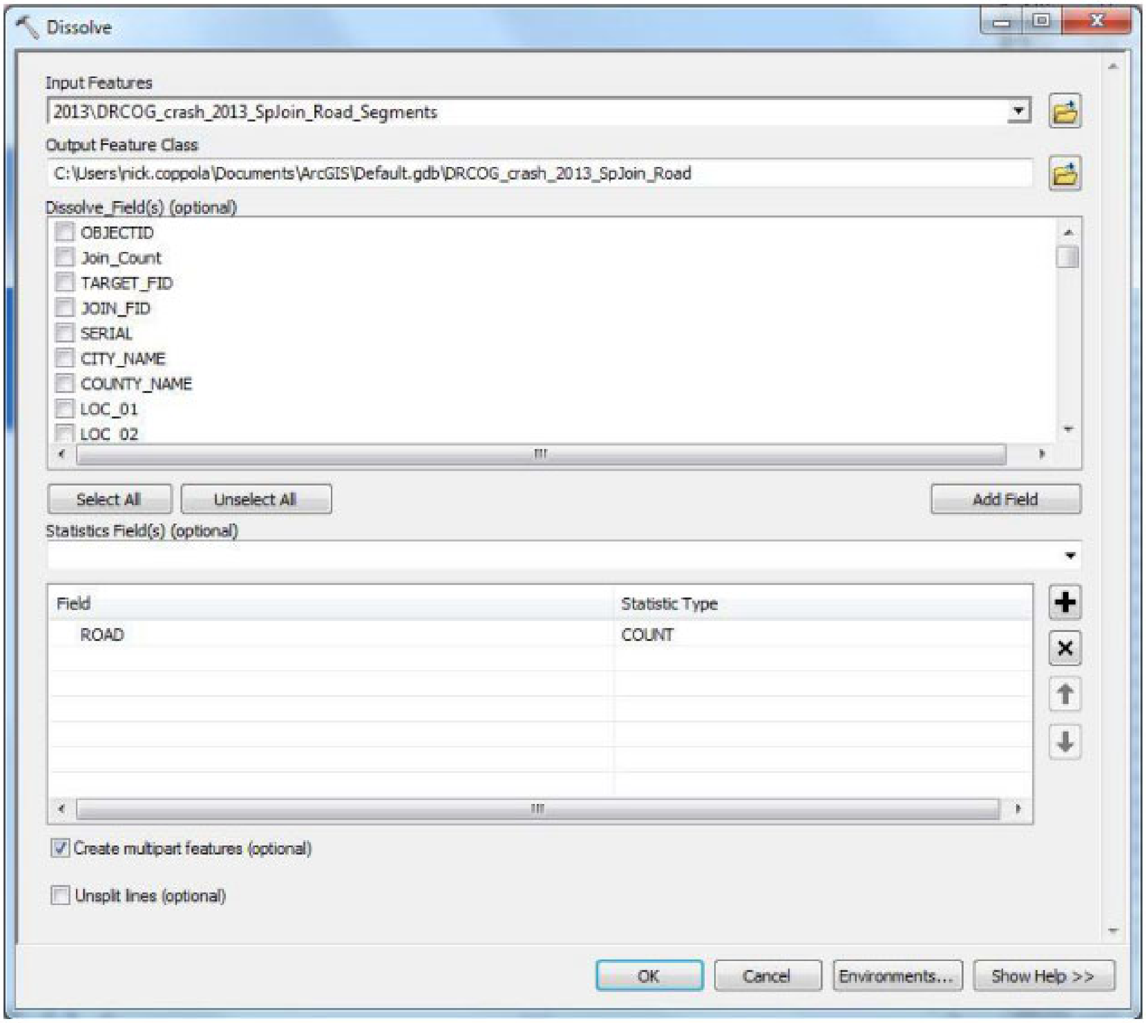
	06	Roundabout	Corridor
	07	Highway Interchange	Not Used
	08	Parking Lot	Not Used

As mentioned, the intersection and corridor area for each road segment was used in the spatial join to find intersecting road segments (see screen shot below)

A spatial join was conducted with the road segment data and the crash data from DRCOG for each year. In order to account for overlapping intersections, the spatial join was "One to Many" to allow for a point to be retained where an intersection with 2 road segments occur.

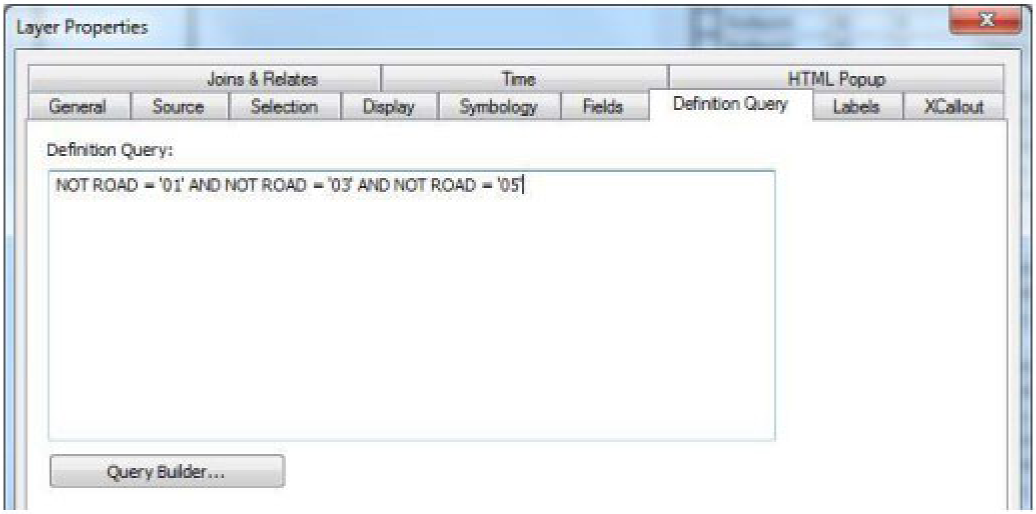


After the spatial join, the points were dissolved and the "ROAD" field was counted to obtain the number of crashes for each road segment.

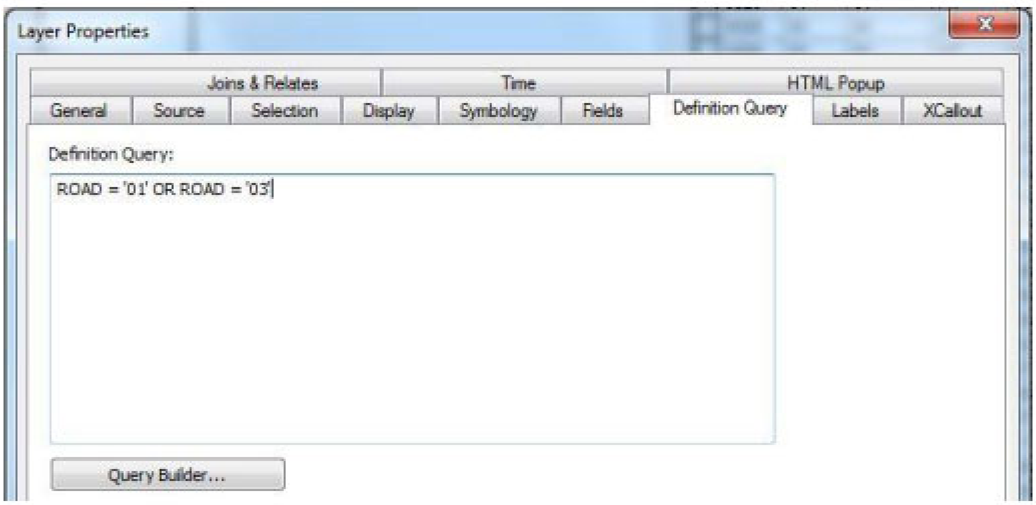


This will create a new point spatial dataset that has counted the number of crashes for each attribute entry in the "ROAD" field. Using the definition query option for the layer in ArcMap, 1 and 3 were queried for intersections and 2, 4, 6, and 7 were queried for corridors. For each definition query, the points were dissolved a second time to obtain the sum for intersection and corridor crashes in each road segment.

Corridor



Intersection



Calculating Corridor Crash Rate

A: Average Number of Crashes per Year

L: Segment Length in Miles

V: Average Daily Traffic Volume

Rate expressed in crashes per Million Vehicle Miles Traveled (MVMT):

$$\frac{(A * 1{,}000{,}000)}{(L * V * 365)}$$

Source: MassDOT Crash Rate Procedures

Calculating Intersection Crash Rate

A: Average Number of Crashes per Year

V: Intersection Daily Approach Volume

Rate expressed in crashes per Million Entering Vehicles (MEV):

$$\frac{(A * 1{,}000{,}000)}{(V * 365)}$$

Source: MassDOT Crash Rate Procedures

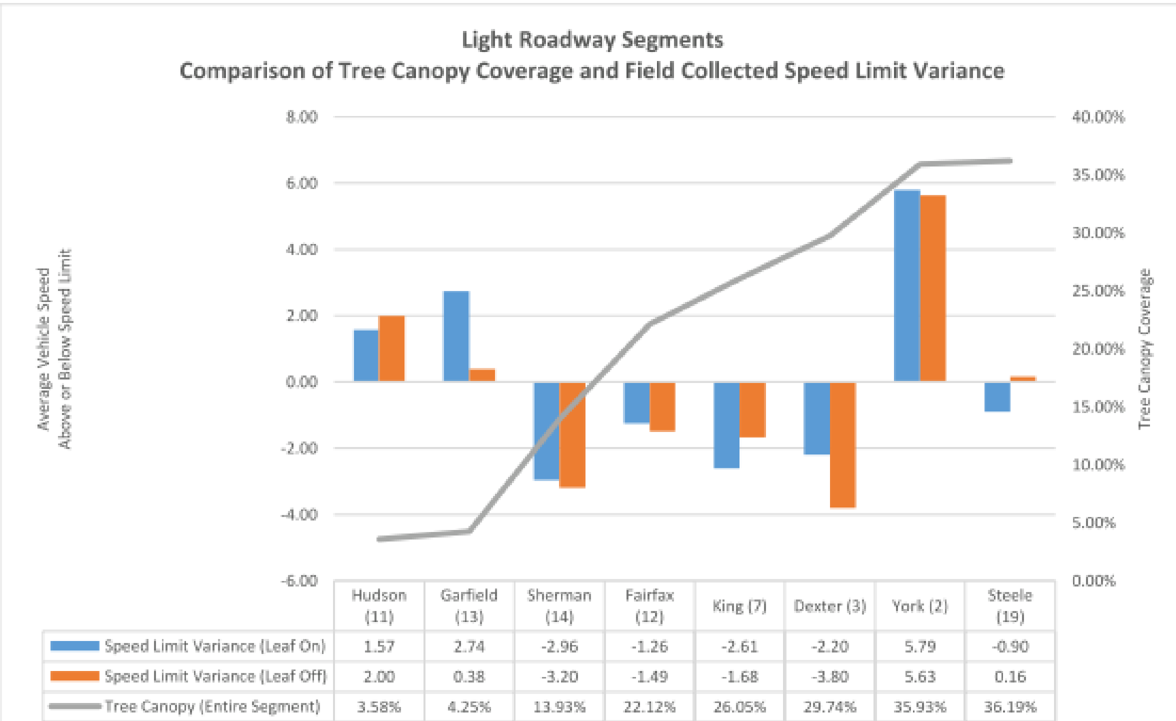
The street segment lengths that were calculated in GIS are available in Appendix G.

Results

Tree Canopy Coverage and Speed Limit Variance

The light and moderate roadways show a trend of slower speeds with corresponding tree *presence* but not necessarily a correspondence to leaves on or off of the trees.

As the light roadway tree canopy increases from 4.25% at Garfield to 13.93% at Sherman, there is a noticeable change from vehicles going over the speed limit on average to vehicles driving at the speed limit or under, with the exception of York. There is no particular trend in average speed decreasing nor is there a trend showing in average speeds when leaves were on or off of the trees.



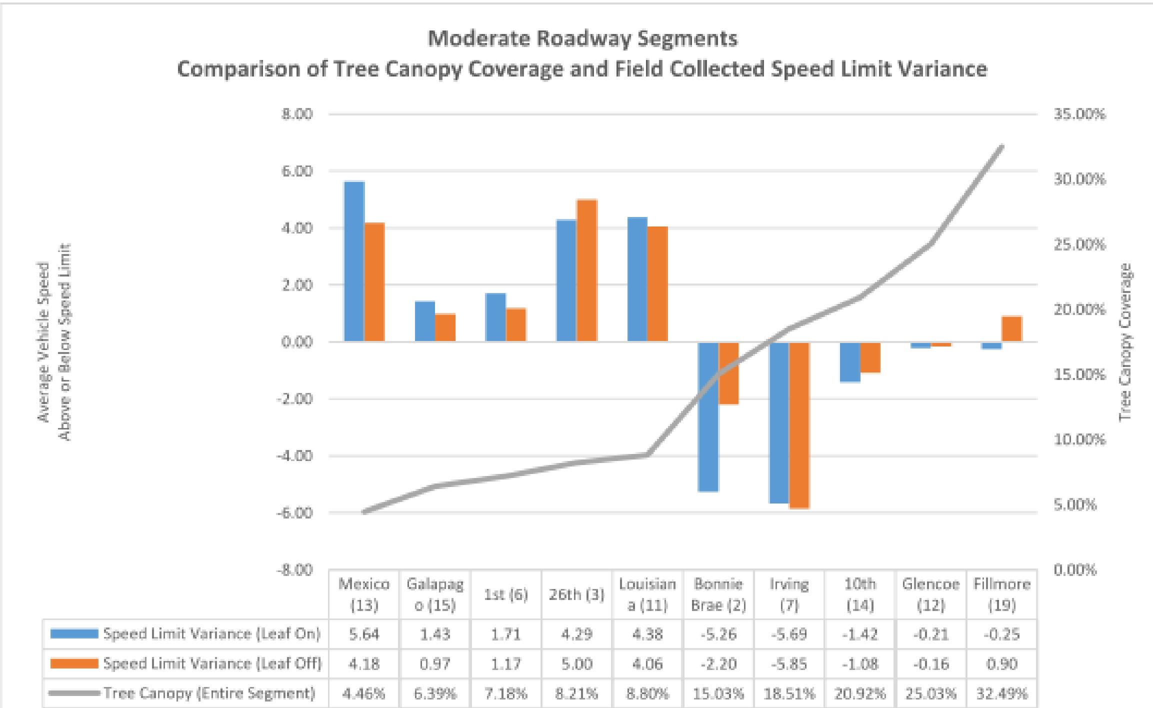
	Hudson (11)	Garfield (13)	Sherman (14)	Fairfax (12)	King (7)	Dexter (3)	York (2)	Steele (19)
Speed Limit Variance (Leaf On)	1.57	2.74	-2.96	-1.26	-2.61	-2.20	5.79	-0.90
Speed Limit Variance (Leaf Off)	2.00	0.38	-3.20	-1.49	-1.68	-3.80	5.63	0.16
Tree Canopy (Entire Segment)	3.58%	4.25%	13.93%	22.12%	26.05%	29.74%	35.93%	36.19%

Based upon further review of York, there are no outlying indicators, based on the characteristics used in this project, to indicate why this road would be an outlier. All light corridors have 25 mph speed limit, two-way operation, 30 or 36 foot primary surface width, and no median; in addition, York's AADT is 593 which lies in the middle of the min and max of 236 and 1366 respectively. Please see the complete comparison below.

Street Name	Speed Limit	Operation	Primary Surface Width	Median	AADT
Fairfax	25	Two-way	30	N	236

Steele	25	Two-way	30	N	892
York	25	Two-way	30	N	593
Dexter	25	Two-way	30	N	439
King	25	Two-way	30	N	248
Hudson	25	Two-way	36	N	263
Garfield	25	Two-way	36	N	610
Sherman	25	Two-way	36	N	1366

As the moderate roadway tree canopy increases from 8.8% at Louisiana to 15.03% at Bonnie Brae, there once again is a noticeable change from vehicles going over the speed limit on average to approximately at the speed limit or under.



	Mexico (13)	Galapago (15)	1st (6)	26th (3)	Louisiana (11)	Bonnie Brae (2)	Irving (7)	10th (14)	Glencoe (12)	Fillmore (19)
Speed Limit Variance (Leaf On)	5.64	1.43	1.71	4.29	4.38	-5.26	-5.69	-1.42	-0.21	-0.25
Speed Limit Variance (Leaf Off)	4.18	0.97	1.17	5.00	4.06	-2.20	-5.85	-1.08	-0.16	0.90
Tree Canopy (Entire Segment)	4.46%	6.39%	7.18%	8.21%	8.80%	15.03%	18.51%	20.92%	25.03%	32.49%

Both the heavy and arterial roads show no indication of effect from tree presence and/or percentage of tree canopy coverage. The results do not show any pattern or trend that would indicate an effect on vehicle speeds when leaves are on or off of the trees.

Tree Canopy Coverage and Average Crash Rates

The results for both road corridor and intersections for all segments did not provide any pattern or trend indicating a correlation between tree canopy coverage and crash rates.

Tree Canopy Coverage and Crash Severity

The lowest level of injury severity is recorded on the State of Colorado Traffic Accident Report is a "Complaint of Injury." Comparing the average number of people with this recordation in an accident from 2010-2013, there was no correlation for either corridor or intersection related injuries at this level and tree canopy.

The second highest level of injury severity is "Evident Non-incapacitating Injury" and the fourth highest level is "Evident Incapacitating Injury." Neither of these severity levels show any correlation between the percentage of tree canopy coverage on road segment corridors or intersections.

The highest level of injury severity is "Fatal." There are a very low number of fatalities reported for both road corridor and intersection segments in this analysis; however, it is worth noting that all fatalities occurred where there was less than 10% canopy coverage.

Conclusion

In closing, this analysis has provided insights and trends that could prove to reveal further information of the effects that trees can have on roadway safety. Light and moderate roadways reveal a trend denoting a shift from average speeds above the speed limit to below the speed limit when tree presence increases.

Extrapolating on this statement, it is also worth noting that the presence of trees appeared to be more of a factor than the presence of leaves. An inference can be made from the tree canopy data, where higher canopy coverage equals greater presence of trees. In turn, roads with a great *presence* of trees may prove to have an effect on and enhance safety whereas canopy coverage based on leaves on or off of trees shows no trend.

A further review of the light roads in this analysis may provide further information pertaining to why York is an outlier in the speed data collected when analyzed with tree presence and canopy coverage as well. In addition, the canopy coverage above 8.8% and below 13.93% could potentially prove to be a tipping point for effective street design resulting in a change of habit by lowering vehicle speed.

Regarding severity levels, no definitive information was able to be extracted from the results; however, fatalities in road corridors and intersections with canopy coverage above and below 10% coverage may prove to be a beneficial analysis.

The spatial data utilized to conduct these analyses covers a considerable time span, which could affect the strength of the results. The tree canopy coverage data is from 2006, crash data is from 2010-2013, and the planimetrics data is from 2015 just to name a few. These datasets cover close to a decade in span and Denver has changed considerably during this time frame. If data could be obtained from one year, this could enhance the integrity of the results.

The raw data obtained may also prove to be beneficial for future research. There is a considerable amount of data and additional analyses that were not covered in this paper which may be a good starting point for a future report.

Overall, quantitative insight has been obtained supporting NACTO's implication that trees may assist in increasing traffic safety. On light and moderate roads, trees appear to slow drivers and on all roads trees could prove to inhibit the level of traffic from reaching fatal.

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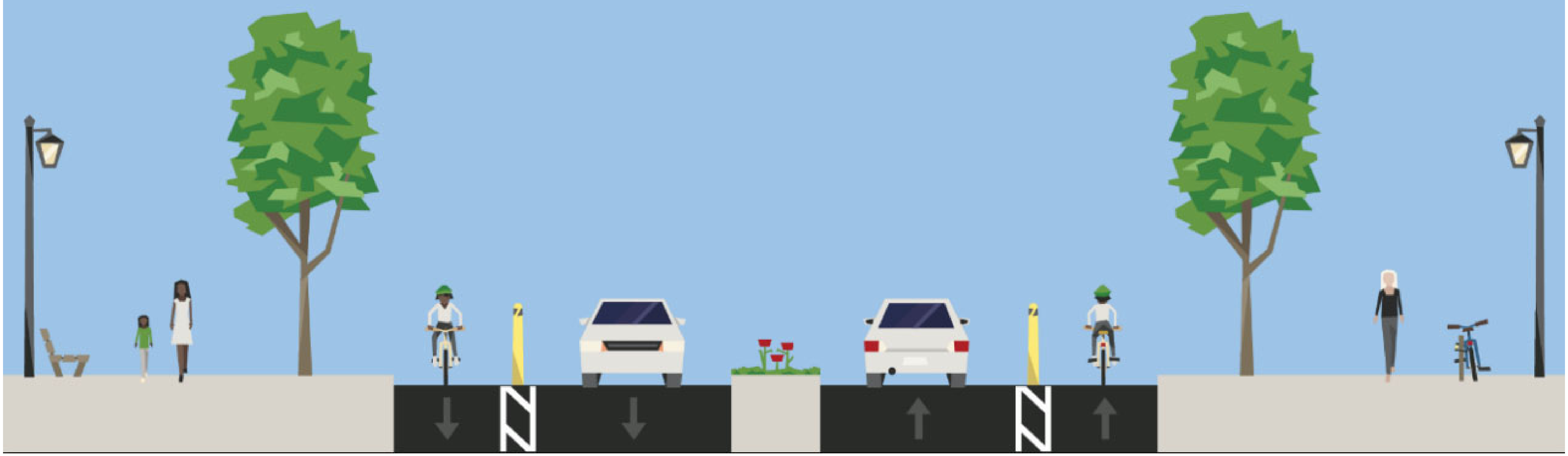
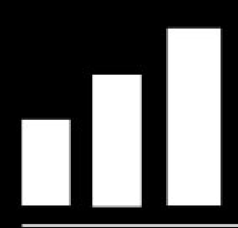
Denver
Street Trees and Road Safety
A Geographic Information Systems Analysis



Road Safety

NHTSA
www.nhtsa.gov

United States
7.2% increase in traffic fatalities
2014-2015



Colorado
11.9% increase in traffic fatalities
2014-2015

Source: NHTSA https://cdan.nhtsa.gov/stsi.htm#

Image Sources: Accident free Icon made by Freepik in people from www.flaticon.com | ***NHTSA icon: http://www.motorauthority.com/news/1098639_new-nhtsa-teams-speed-response-after-gm-ignition-switch-recall***

Road Safety

Denver County
21.4% increase in traffic fatalities
2014-2015

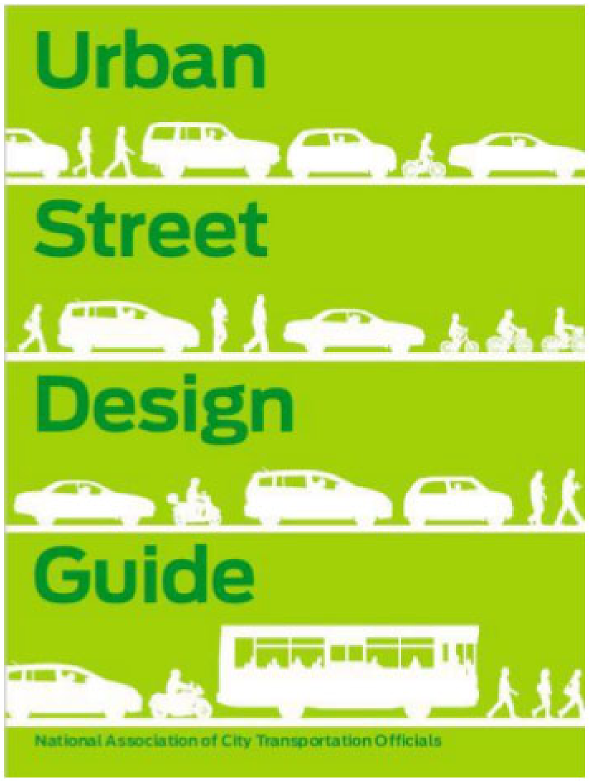
https://cdan.nhtsa.gov/SASStoredProcess/guest?_program=%2FUATTest%2FSTSI

Denver County
Overall crashes have increased
15,810 to 16,928
2014-2015

https://cdan.nhtsa.gov/SASStoredProcess/guest?_program=%2FUATTest%2FSTSI

Image Sources: Accident free Icon made by Freepik in transport from www.flaticon.com | NHTSA icon: http://www.motorauthority.com/news/1098639_new-nhtsa-teams-speed-response-after-gm-ignition-switch-recall

Road Safety



Street Trees

- Speed Reduction Mechanism
- Healthy Ecosystem
- Aesthetic Appeal

Image Sources: Tree free Icon made by Freepik in nature from www.flaticon.com | NACTO Urban Street Design Guide cover

Purpose

What correlation(s) may exist between tree canopy coverage and traffic safety

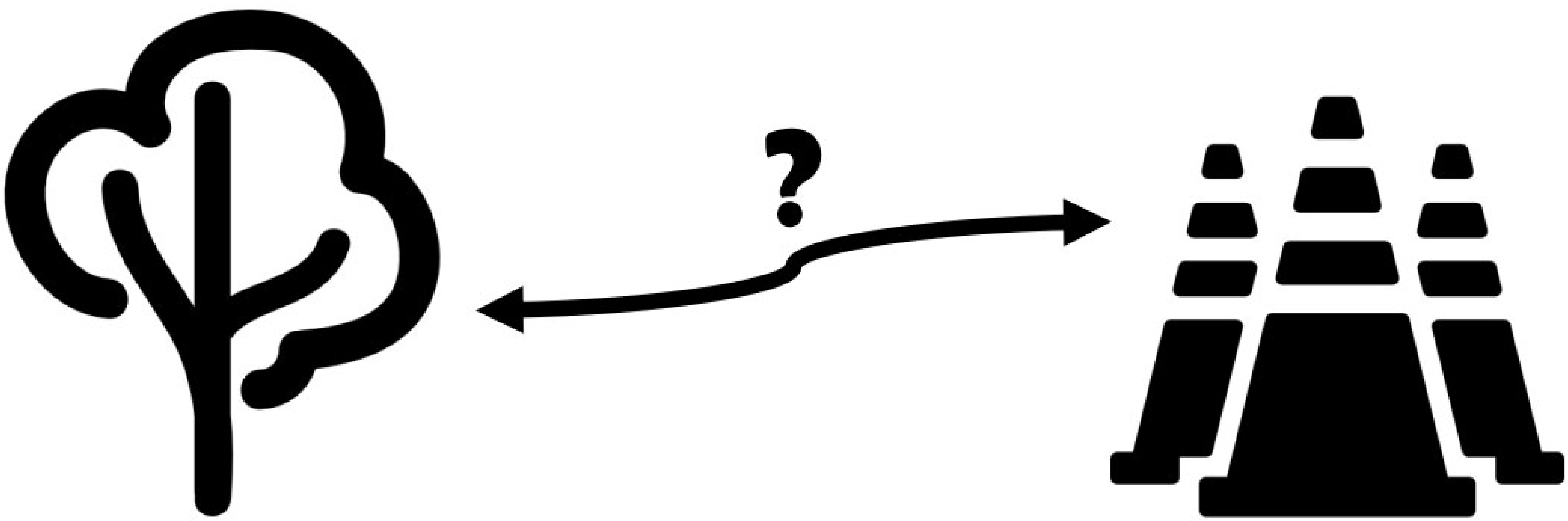
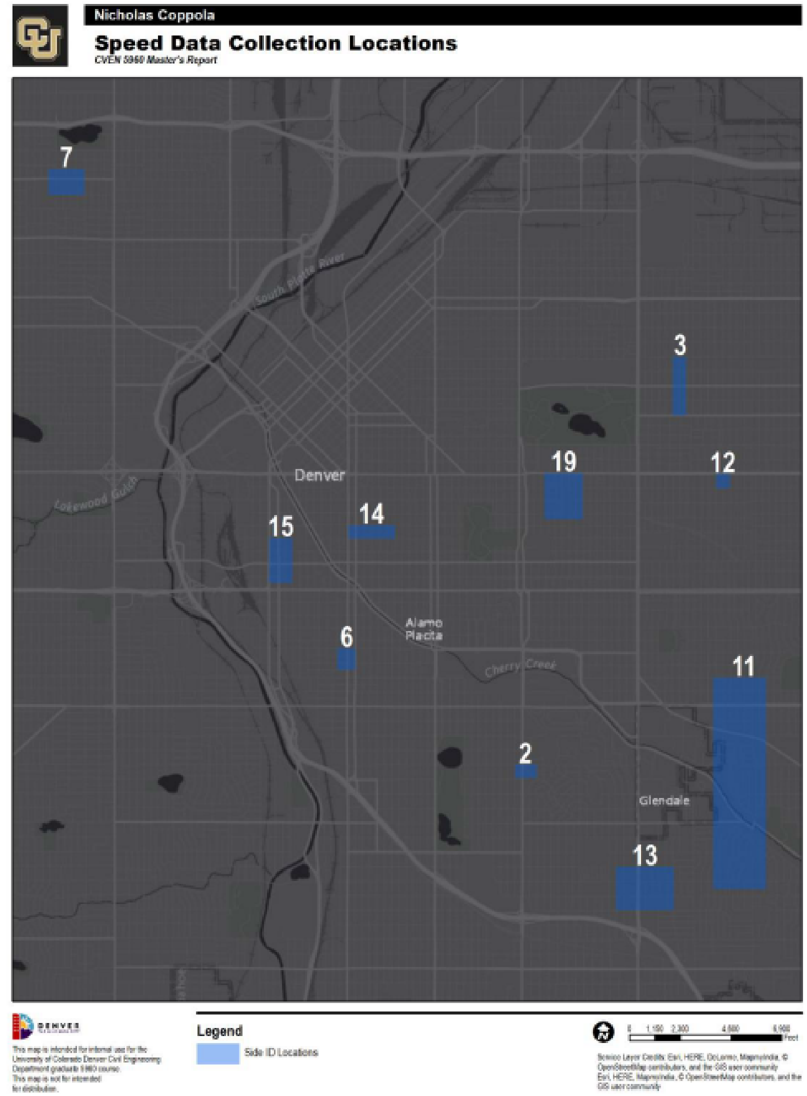


Image Sources: Tree gross icon free Icon made by Freepik *in* **nature from** www.flaticon.com | *Traffic cones free Icon made by* Freepik *in* **transport from** www.flaticon.com

Locations

SITEID	FULL_NAME	CROSS_1	CROSS_2	TYPE
2	University Blvd	Exposition	Ohio	Arterial
2	Exposition			Heavy
2	Bonnie Brae			Moderate
2	York			Light
3	23rd Avenue	Cherry	Dexter	Arterial
3	Montview			Heavy
3	26th			Moderate
3	Dexter			Light
6	Broadway	1st	Bayaud	Arterial
6	Lincoln			Heavy
6	1st			Moderate
6	~~Irvington~~	-	-	~~Light~~
7	44th Avenue	Meade	King	Arterial
7	Lowell			Heavy
7	Irving			Moderate
7	King			Light
11	Holly Street	Ivanhoe	Gunnison	Arterial
11	Florida			Heavy
11	Louisiana			Moderate
11	Hudson			Light

SITEID	FULL_NAME	CROSS_1	CROSS_2	TYPE
12	Colfax Avenue	Elm	Forest	Arterial
12	14th			Heavy
12	Glencoe			Moderate
12	Fairfax			Light
~~13~~	~~Colorado Blvd~~	~~Louisiana~~	~~Mexico~~	~~Arterial~~
13	Florida			Heavy
13	Mexico			Moderate
13	Garfield			Light
14	Broadway	8th	12th	Arterial
14	11th			Heavy
14	10th			Moderate
14	Sheman			Light
15	Santa Fe Drive	12th	7th	Arterial
15	Kalamath			Heavy
15	Galapago			Moderate
~~15~~	~~Inca~~	-	-	~~Light~~
19	Colfax Avenue	York	Cook	Arterial
19	14th			Heavy
19	Fillmore			Moderate
19	Steele			Light



Data Details

Spatial and Attribute Data Sources

- Colorado Department of Transportation (CDOT)
- Denver Regional Council of Governments (DRCOG)
- The City and County of Denver
- The University of Colorado Denver

Data Details

Colorado Department of Transportation (CDOT)

- Highways
  - Polyline spatial data
  - Transportation Colorado Roadway Information System (TCORIS)
    - Attribute data
    - Lane quantity and width

- Major Roads
  - Polyline spatial data
  - Public roads classified as arterial and collector public

- Local Roads
  - Polyline spatial data
  - Public roads classified as local

Data Details

The City and County of Denver

- Tree Canopy
  - Polygon spatial data
  - 2006 "QuickBird 2 foot pixel satellite imagery"

- Street Centerline
  - Polyline spatial data
  - City and County of Denver streets

Data Details

Denver Regional Council of Governments (DRCOG)

- Crash Data
  - Point spatial data
  - 2010-2013 location for each crash reported originating from the State of Colorado Traffic Accident Report Forms

- Planimetric Data
  - Polygon spatial data
  - Edge of pavement and sidewalk data created from Denver Regional Aerial Photography Project (DRAPP) 2014 Aerial Imagery

Data Details

The University of Colorado Denver

Previously Collected Data

- Street Locations
  - Attribute data

- Annual Average Daily Traffic (AADT)
  - Attribute data

Data Details

The University of Colorado Denver

Field Collected Speed Data

Protocol

- Passenger Cars, Minivans, and Light Trucks Only
- Observation / Collection from parked car, concealed location, or residence
- Weather Conditions: Dry and Clear
- 2 Field Sessions: Winter (Leaf-Off) and Summer (Leaf-On)

Methods

Spatial Data Preparation

- Street segment characteristics
- Determine street segment start and end point
- Creating primary surface area for intersection and corridor
- Calculate Average Number of Crashes per Year
- Calculate Intersection and Corridor Crash Rate

Methods

Street Segment Characteristics

- Speed Limit
- Operation (one-way or two-way)
- Primary Surface Width
- Median (absent or present)

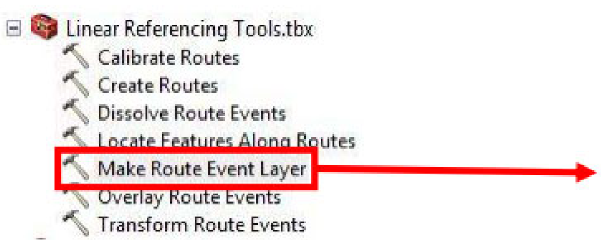
Separate Preparation Methods

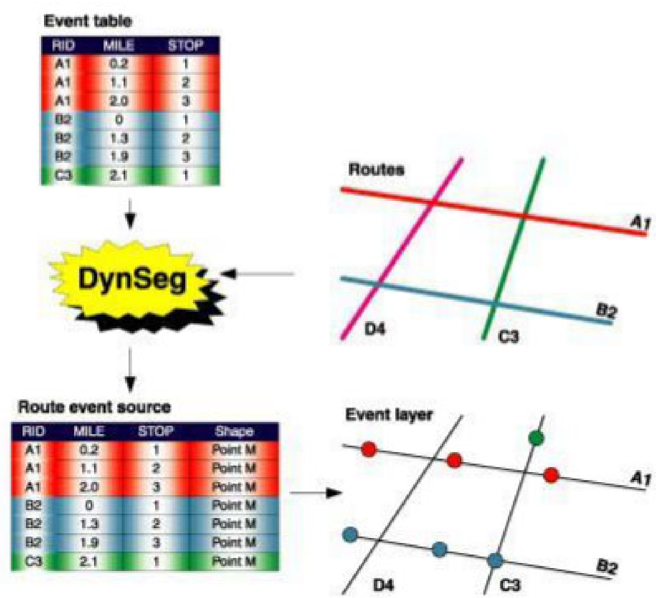
- Highways
- Major and Local Roads

Methods

Street Segment Characteristics (Highways)

- Geospatial Tool: Make Route Event Layer
  - Spatial Data: Highways
  - Table: TCORIS





Methods

Street Segment Characteristics (Highways)

- Calculate Primary Surface Width
  - TCORIS Attributes

Field Name	Brief Description
PriThruLnQty	Thru Lane Quantity (Primary Direction of Traffic)
PriThruLnWd	Thru Lane Width (Primary Direction of Traffic)
SecThruLnQty	Thru Lane Quantity (Secondary Direction of Traffic)
SecThruLnWd	Thru Lane Width (Secondary Direction of Traffic)
PriLTurnWd	Left Turn Lane Width (Primary Direction of Traffic)
PriLTurnQty	Left Turn Lane Quantity (Primary Direction of Traffic)
SecLTurnWd	Left Turn Lane Width (Secondary Direction of Traffic)
SecLTurnQty	Left Turn Lane Quantity (Secondary Direction of Traffic)
PriAuxLnWd	Primary Auxiliary Lane Width (Primary Direction of Traffic)
PriAuxLnQty	Primary Auxiliary Lane Quantity (Primary Direction of Traffic)
SecAuxLnWd	Auxiliary Lane Width (Secondary Direction of Traffic)
SecAuxLnQty	Auxiliary Lane Quantity (Secondary Direction of Traffic)
PriOutShldWd	Primary Outside Shoulder Width (Primary Direction of Traffic)
SecOutShldWd	Outside Shoulder Width (Secondary Direction of Traffic)
PriInShldWd	Left Inside Shoulder Width (Primary Direction of Traffic)
SecInShldWd	Left Inside Shoulder Width (Secondary Direction of Traffic)
MedianWd	Median Width

Methods

Street Segment Characteristics (Highways)

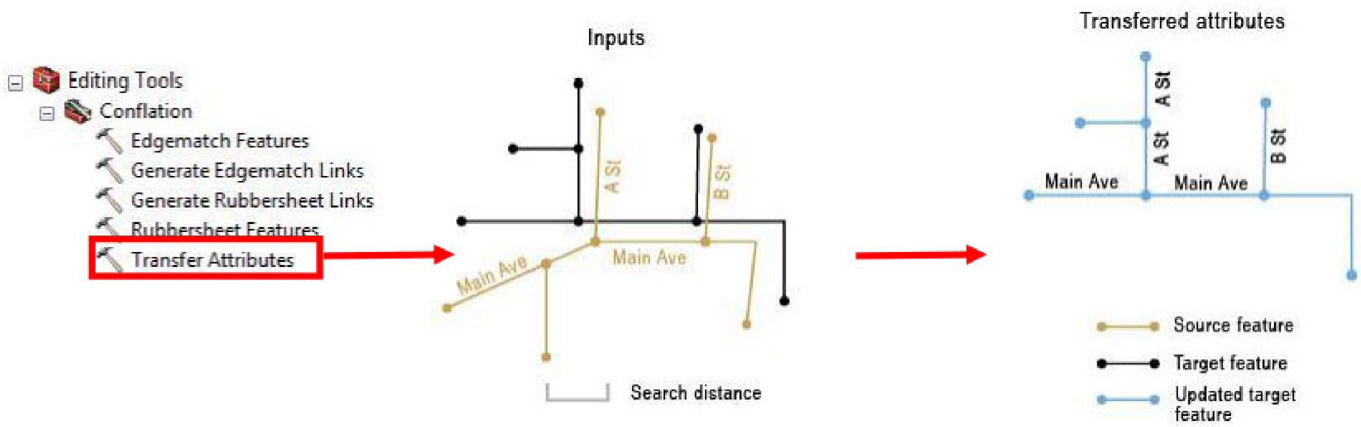
- Median simplified to "Y" or "N"

Median (TCORIS)	Calculated Field
1 None	N
12 Painted - No Vehicles	Y
13 Parking	
14 Level	
21 Depressed	
31 Raised (no curb)	
41 Raised Curb	
52 Channelized - Raised Curb	
54 Channelized - Painted	
55 HOV Reversible	

Methods

Street Segment Characteristics (Local and Major Roads)

- Geospatial Tool: Transfer Attributes
  - Spatial Data: CDOT Major Roads and Local Roads, The City and County of Denver street centerline



Methods

Street Segment Characteristics (Highways, Local Roads, and Major Roads)

- Dissolve spatial data
  - Fields
    - Route
    - Speed Limit
    - Median
    - Operation
    - Primary Surface Width

Methods

Determine street segment start and end point

- Origin for each segment: Speed Data Collection Location

- 4 Characteristics
  - Speed limit
  - Operation (one-way or two-way)
  - Median (present or absent)
  - Primary surface width

- Spatial Data: Dissolved highway, major road, and local road data from “preparation” in prior section

- Extent: When any other 4 characteristics change

Methods

Determine street segment start and end point

QA/QC

Example

Point of origin where speed data was collected
Site ID 14 | Arterial | Broadway

FULLNAME	SPEEDLIMIT	ONEWAY	MEDIAN	PRISURFWD
N BROADWAY	30	1	N	72

Methods

Determine street segment start and end point

QA/QC

Example

Two separate spatial features with the same characteristics
Spearated due to change in street name

FULLNAME	SPEEDLIMIT	ONEWAY	MEDIAN	PRISURFWD
N BROADWAY	30	1	N	72
S BROADWAY	30	1	N	72

Methods

Determine street segment start and end point

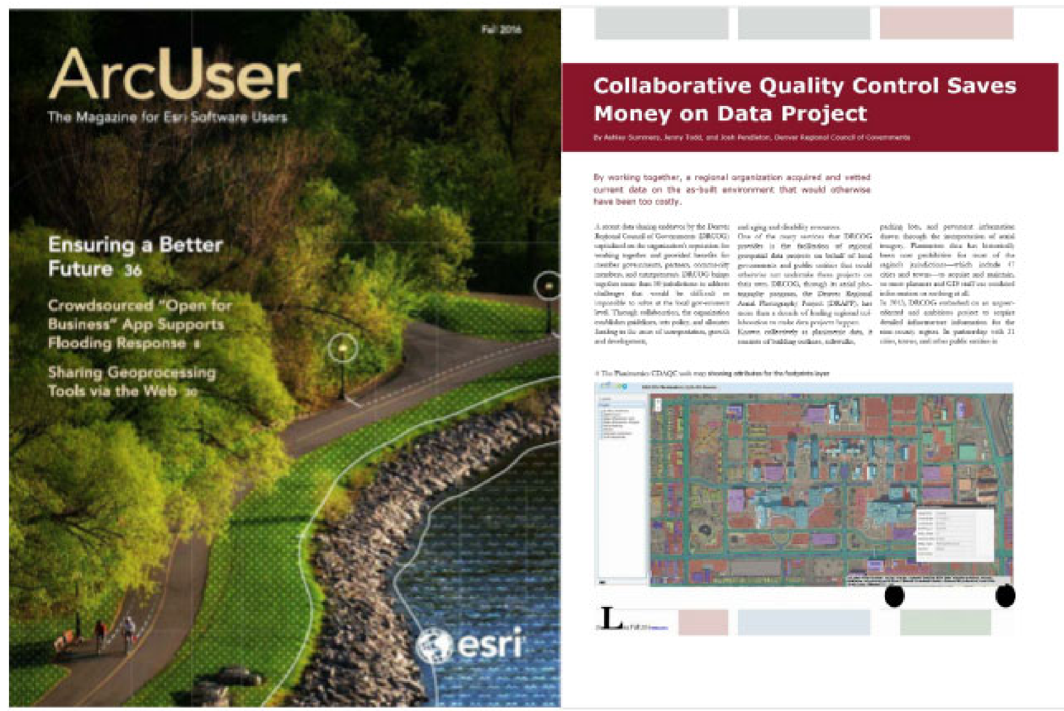
Creating Primary Surface Area

Source: DRCOG https://drcog.org/services-and-resources/data-maps-and-modeling/gis-maps/denver-regional-aerial-photography-project

Methods

Determine street segment start and end point

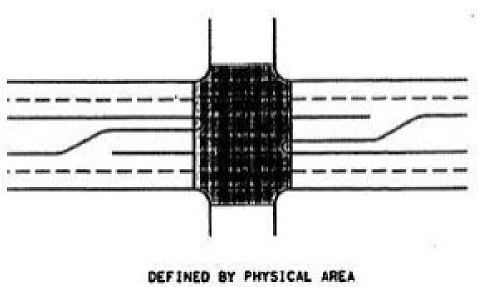
Creating Primary Surface Area



Methods

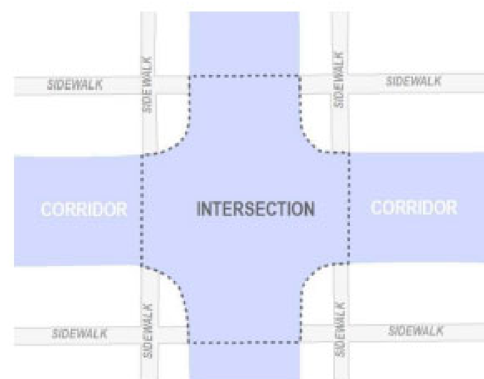
Creating Primary Surface Area at an intersection

AASHTO Green Book
Intersection Depicted by physical area



Source: AASHTO Green Book Page 557

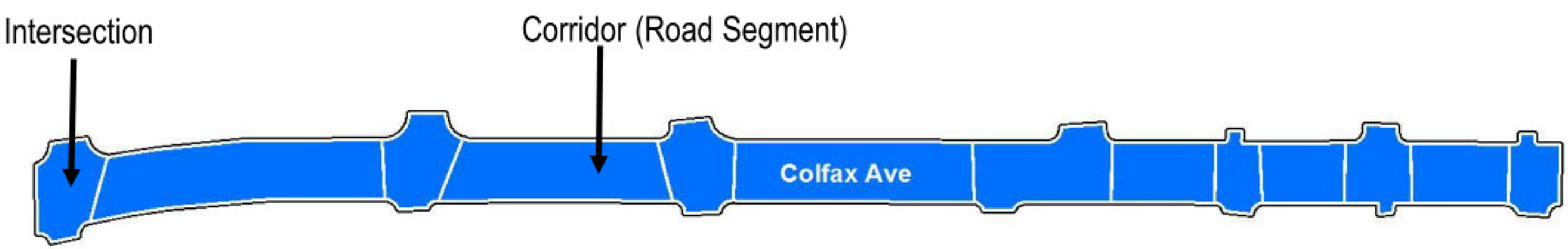
Digitized GIS
Intersection created from DRCOG Planimetrics



Methods

Creating Primary Surface Area at an intersection and corridor

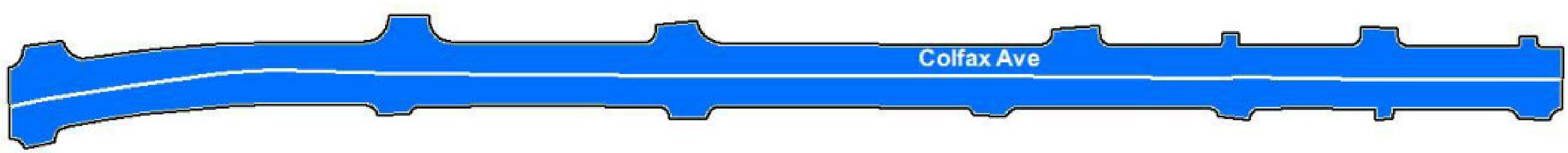
Example of Intersection and Corridor along Site ID 19 Colfax Avenue



Methods

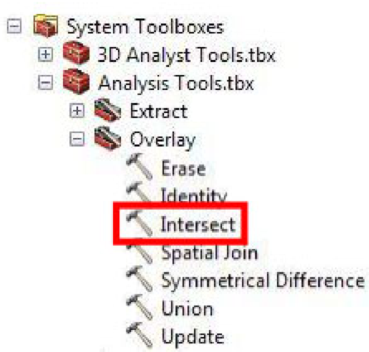
Creating Primary Surface Area and Street Segment Length

Example of entire street Site ID 19 Colfax Avenue

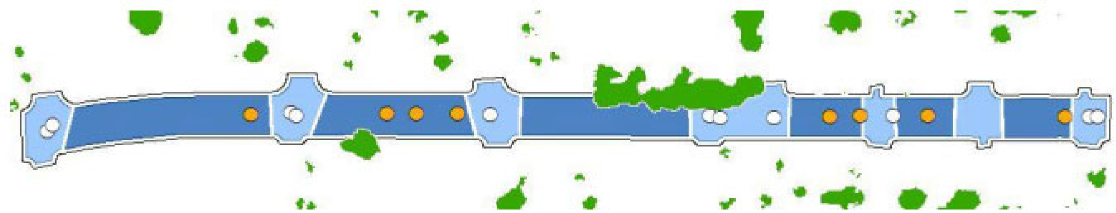


Methods

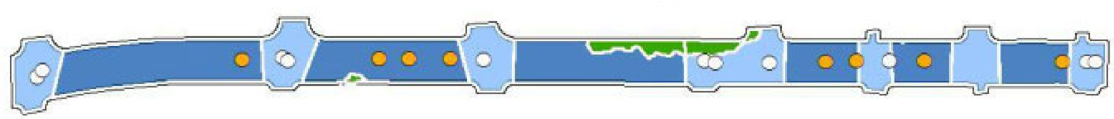
Calculate Tree Canopy Coverage



Colfax Ave
Original Tree Canopy Data



Colfax Ave
Intersect Tree Canopy Data



SiteID	Type	StreetName	Cross_1	Cross_2	UCD_PriSurfType	SHAPE_Area	RdSegArea	PctCanopy	UID *	UID2 *
19	Arterial	Colfax Ave	York	Cook	Intersection	196.865275	4281.460803	0.045981	19 Arterial Intersection Colfax Ave	19 Arterial Colfax Ave
19	Arterial	Colfax Ave	York	Cook	Road Segment	285.538044	7011.381271	0.040725	19 Arterial Road Segment Colfax Ave	19 Arterial Colfax Ave

Methods

Crash Data Selection

Example: 2010 DRCOG crash data

Methods

Calculate Average Number of Crashes per Year
2010-2013 DRCOG crash data

Screen shot from block D on the "State of Colorado Traffic Accident Report"

D. ROAD DESCRIPTION

01. At Intersection
02. Driveway Access Related
03. Intersection Related
04. Non-Intersection
05. Alley Related
06. Roundabout
07. Highway Interchange
08. Parking Lot

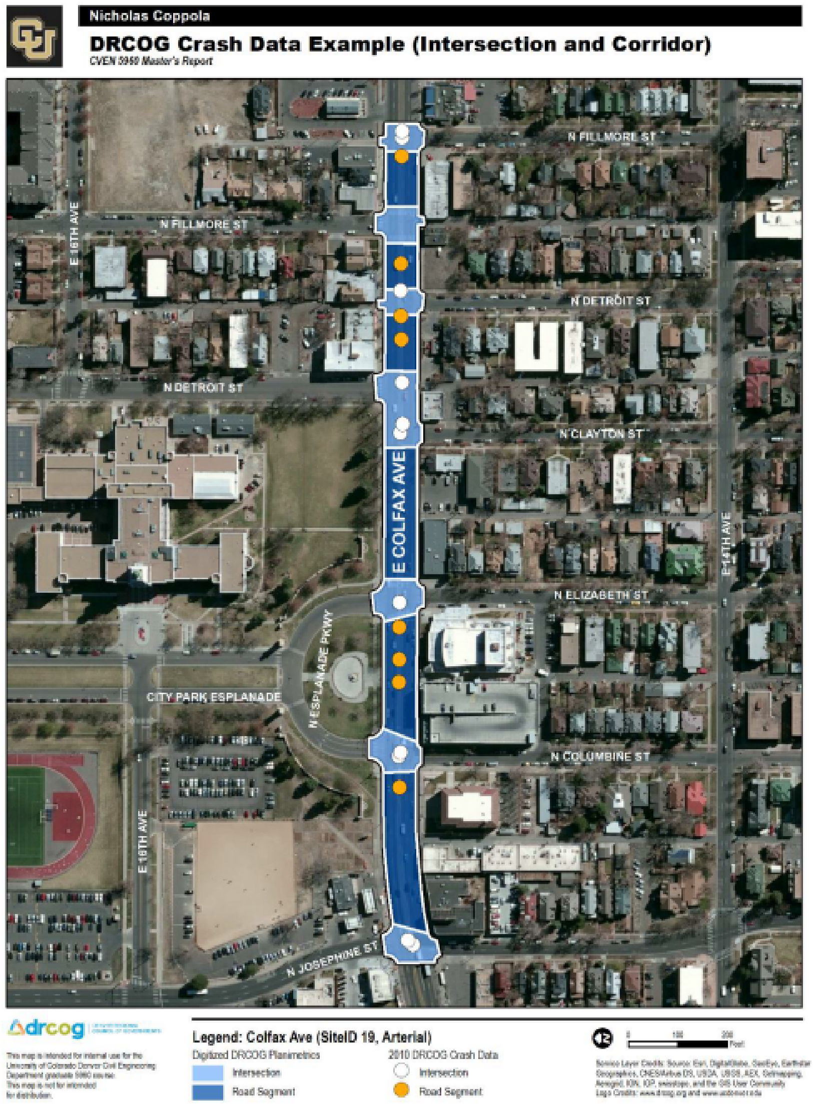
GIS data used for Intersection or Corridor in Analyses

Field Name	Value	Definition	Query
Road	01	At Intersection	Intersection
	02	Driveway Access Related	Corridor
	03	Intersection Related	Intersection
	04	Non-Intersection	Corridor
	05	Alley Related	Not Used
	06	Roundabout	Corridor
	07	Highway Interchange	Not Used
	08	Parking Lot	Not Used

Methods

Calculate Average Number of Crashes per Year

2010-2013 DRCOG crash data



Methods

Calculating Corridor and Intersection Crash Rate

Corridor

A: Average Number of Crashes per Year

L: Segment Length in Miles

V: Average Daily Traffic Volume

Rate expressed in crashes per Million Vehicle Miles Traveled (MVMT):

$$\frac{(A * 1{,}000{,}000)}{(L * V * 365)}$$

Source: MassDOT Crash Rate Procedures

Intersection

A: Average Number of Crashes per Year

V: Intersection Daily Approach Volume

Rate expressed in crashes per Million Entering Vehicles (MEV):

$$\frac{(A * 1{,}000{,}000)}{(V * 365)}$$

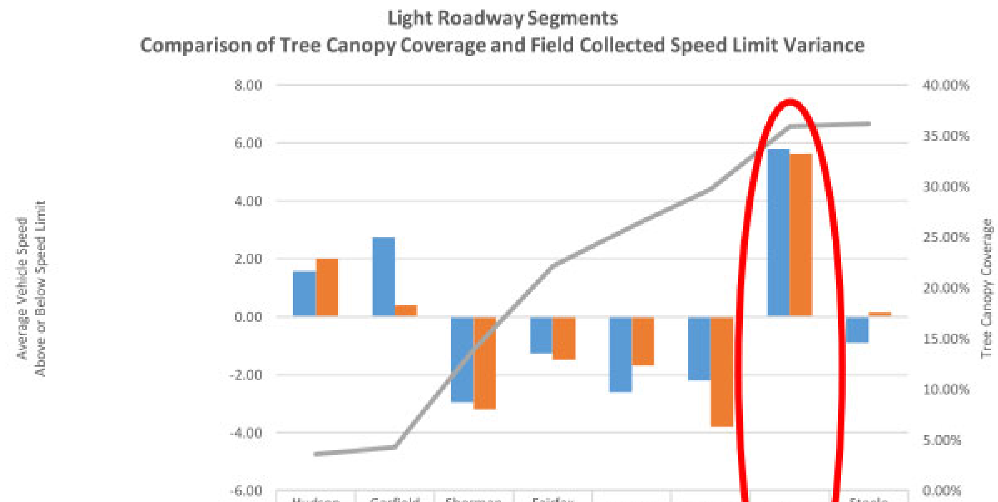
Source: MassDOT Crash Rate Procedures

Results

Tree Canopy Coverage and Speed Limit Variance

Light Roadways

Trend of slower speeds with corresponding tree *presence* not necessarily a correspondence to leaves on or off of the trees



	Hudson (11)	Garfield (13)	Sherman (14)	Fairfax (12)	King (7)	Dexter (3)	York (2)	Steele (19)
Speed Limit Variance (Leaf On)	1.57	2.74	-2.96	-1.26	-2.61	-2.20	5.79	-0.90
Speed Limit Variance (Leaf Off)	2.00	0.38	-3.20	-1.49	-1.68	-3.80	5.63	0.16
Tree Canopy (Entire Segment)	3.58%	4.25%	13.93%	22.12%	26.05%	29.74%	35.93%	36.19%

Results

Tree Canopy Coverage and Speed Limit Variance

Review of York

No outlying indicators, based on the characteristics used in this project, to indicate why this road would be an outlier

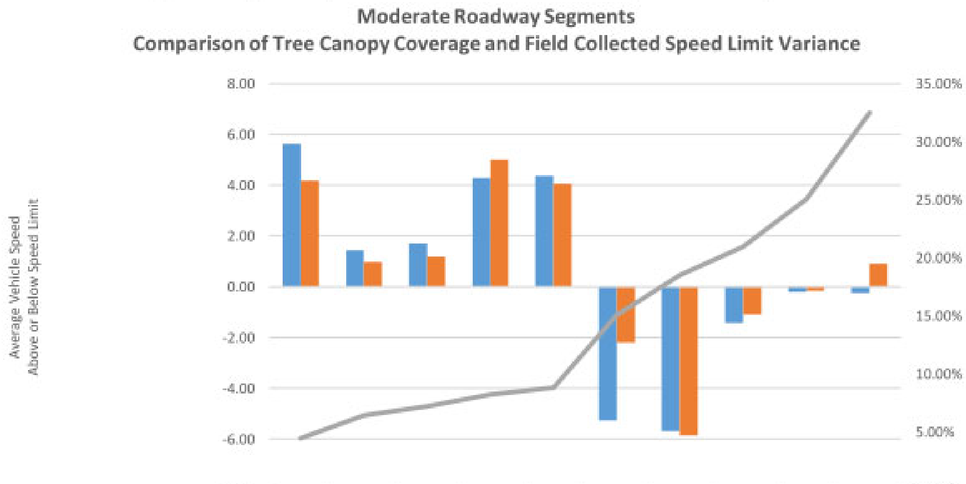
Street Name	Speed Limit	Operation	Primary Surface Width	Median	AADT
Fairfax	25	Two-way	30	N	236
Steele	25	Two-way	30	N	892
York	25	Two-way	30	N	593
Dexter	25	Two-way	30	N	439
King	25	Two-way	30	N	248
Hudson	25	Two-way	36	N	263
Garfield	25	Two-way	36	N	610
Sherman	25	Two-way	36	N	1366

Results

Tree Canopy Coverage and Speed Limit Variance

Moderate Roadways

Trend of slower speeds with corresponding tree *presence* not necessarily a correspondence to leaves on or off of the trees



	Mexico (13)	Galapago (15)	1st (6)	26th (3)	Louisiana (11)	Bonnie Brae (2)	Irving (7)	10th (14)	Glencoe (12)	Fillmore (19)
Speed Limit Variance (Leaf On)	5.64	1.43	1.71	4.29	4.38	-5.26	-5.69	-1.42	-0.21	-0.25
Speed Limit Variance (Leaf Off)	4.18	0.97	1.17	5.00	4.06	-2.20	-5.85	-1.08	-0.16	0.90
Tree Canopy (Entire Segment)	4.46%	6.39%	7.18%	8.21%	8.80%	15.03%	18.51%	20.92%	25.03%	32.49%

Results

Tree Canopy Coverage and Speed Limit Variance

Heavy and Arterial Roads

- No indication of effect from tree presence and/or percentage of tree canopy coverage
- No pattern or trend that would indicate an effect on vehicle speeds when leaves are on or off of the trees

Results

Tree Canopy Coverage and Average Crash Rates

Corridor

No indication of effect from tree presence and/or percentage of tree canopy coverage

Intersection

No indication of effect from tree presence and/or percentage of tree canopy coverage

Results

Tree Canopy Coverage and Crash Severity

Level 1 "Complaint of Injury"

No correlation for either corridor or intersection related injuries

Level 2 "Evident Non-incapacitating Injury"

No correlation for either corridor or intersection related injuries

Level 3 "Evident Capacitating Injury"

No correlation for either corridor or intersection related injuries

Level 4 "Fatal"

No correlation for either corridor or intersection related injuries

Note: All fatalities occurred where there was less than 10% canopy coverage

Conclusion

- Light and moderate roadway tree presence = slower drivers and potential increased safety
- Greater *presence* of trees = enhanced safety
- Trees could prove to inhibit the level of traffic from reaching fatal
- Canopy coverage based on leaves on or off of trees shows no trend
- Raw data obtained may prove to be beneficial for future research

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GIS Data Source Icons: www.ucdenver.edu, www.drcog.org, www.cdot.gov, www.denvergov.org