B6
Improving the Cyclist Experience

MAPPING BICYCLE FACILITIES BY LEVELS OF TRAFFIC STRESS

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Jurisdictions in the San Diego region aim to improve cycling as a viable mode of transportation, and to provide continuous bikeways and increase cycling trips. Provision of bicycle facilities is generally measured by facility type; however, bicycle facilities of the same type are not created equal. Studies show that roadway characteristics such as traffic speed, road size, and type influence bicyclists' traffic stress levels and can affect what types of riders are willing to travel certain routes.

This research uses ArcGIS to map roadway data gathered from the San Diego Regional Data Warehouse, and categorizes road segments into traffic stress levels based on traffic speed, roadway classification, bicycle facility type, and slope steepness. This study also creates an origin-destination matrix which quantifies the relative numbers of locations accessible under each traffic stress network.

Introduction

The San Diego region contains a large network of bicycle infrastructure, which planners continue to expand in efforts to increase ridership. However, not all bicycle facilities of the same type are equal. Studies show that factors such as traffic speeds, road widths, slope grades, presence and turnover of on-street parking, obstructions in the bike lane, pavement quality, and traffic volumes all affect bicyclists' comfort levels and influence the likelihood of a bicyclist traveling a particular route. These factors vary even among facilities of the same type – yet, evaluation of provision of bicycle facilities is generally based on facility type alone. This research proposes using road parameters to quantify existing bicycle facilities.

The City of San Diego classifies all bicycle lanes, or lanes painted on roadways to the right of vehicle lanes, as "Class 2" facilities. However, a Class 2 facility along a road on which traffic travels at 50 miles per hour (mph) creates different perceptions of safety for individuals travelling along it from a facility alongside a 30-mph road. While some individuals are more tolerant of high traffic speeds than others, individuals adjacent to 50-mph traffic bear inherently greater risks than individuals adjacent to 30-mph traffic (AAA Foundation). The speed differential between a vehicle and a bicyclist or pedestrian affects the risk of injury or death associated with a possible collision. The risk of death borne by a pedestrian struck by a vehicle is 10% when the vehicle is traveling at 23 mph, 25% at 32 mph, 50% at 42 mph, 75% at 50 mph, and 90% at 58 mph (AAA Foundation, 2011). Faster-moving vehicles also pose a shorter time window for a bicyclist to change lanes, respond to obstacles within the roadway, or anticipate oncoming traffic.

Other important factors include traffic volumes, lane and roadway widths, number of lanes, number of traffic signals, pavement quality, slope grades, lighting, tree coverage, street parking, sidewalk presence, nearby crime rates, and the presence of free-flow right turn lanes. These factors can vary among bicycle facilities of the same type. These discrepancies, created by external factors upon bicycle facilities that infrastructure managers classify as equal, cause confusion on both ends. Bicycle infrastructure managers may believe they are providing adequate facilities to maintain mobility for bicycle travel for different members of the population by including bike lanes, paths, and routes. However, individuals' comfort levels may cause them to discriminate between equally-classified facilities in ways that infrastructure managers may not anticipate. This research proposes to quantify San Diego's bicycle facilities by the levels of stress they create in order to provide a clearer picture of which user types are currently served by the bicycle network.

Literature Review

The San Diego region currently faces long peak-hour delays through traffic congestion, as well as an approximately 42% projected population increase by 2050 (SANDAG, 2010). A study by the Surface Transportation Policy Project (STPP) found that while vehicular congestion exists in many metropolitan areas, its effects on day-to-day life on residents vary significantly based on the viability of other modes of transportation (*4*). Polling data indicates that 69.3% of San Diegans would be "very likely" to cycle more if provided with more bike lanes on major streets (City of San Diego, 2011). With realization spreading across the nation of the need for multi-modal facilities, researchers have been working toward defining critical metrics about bicycle infrastructure and user preference, for the purpose of improving bicycle facilities and increasing bicycle travel.

Quantification of bicycle infrastructure

Much of the urban development on the west coast has occurred with influence from the automobile (Melosi, n.d.). As a result, transportation planning for the past several decades has focused on decreasing automobile travel times, involving large multilane corridors and arterial streets prioritizing automobile travel, unintentionally at the expense of other modes (Litman, 2014). This mobility and auto-centric emphasis has led to performance measures which further widen the gap between automobiles and other modes of travel, such as vehicle level of service (LOS) measures, lane and road widths, and vehicular travel times (Litman, 2014). With performance measures focused on automobile travel times, traffic management policy has tended toward the widening of lanes, expansion of parking, and general development of vehicle-scale areas.

Litman proposes transportation performance measures which emphasize *accessibility* rather than *mobility* – that is, emphasizing the ability of individuals to access needed facilities, rather than the ability of motor vehicles to traverse the system. Litman states that the sheer quantity and quality of available data on automobile travel has often led planning trends and decisions to form a bias toward optimizing automobile travel conditions. Some of the recommended changes in performance measurement include measuring delays in pedestrian and bicycle travel (in addition to motor vehicle delays), factoring parking costs when evaluating costs of vehicle ownership, including multi-modal convenience and comfort factors (as opposed to only accounting for automobile convenience and comfort), and measuring crash rates per capita (rather than only per vehicle-mile, which does not account for crashes caused by induced vehicle travel). Use of these performance measures would allow planners to see what changes would maximize the efficiency of the existing transportation system through more quickly and easily transporting a greater number of people rather than vehicles (Litman, 2014).

To better incorporate performance measures into bicycle facility management, this study replicates a similar research project conducted in the City of San José, in which Mekuria et al. (2012) classify surface streets and intersections by level of traffic stress to bicyclists. The San José study quantified the connectivity of various stress levels within the city's existing bicycling network using a regional street database with data on speed limits, functional classes, and lane, curb-to-curb, and median widths. It also used a regional traffic signal database, a regional map of bicycle and pedestrian facilities, and field measurements of bicycle lane width. Mekuria et al. ultimately generated a bicycle network map of San José and portions of neighboring cities, showing available bicycle facilities for each level of traffic stress (LTS). These maps showed that without improvements, areas at the lowest levels of traffic stress were isolated from one another, due to the lack of low-stress corridors (Mekuria et al., 2012).

The Mekuria study presents a valuable framework for measuring comfort and accessibility that can be applied to San Diego's infrastructure. Additional sections in the present study will discuss which elements of the San José study were replicated for this research and which elements differ.

Current research quantifying bicycle network efficiency and effectiveness from a user perspective is limited. A study by Landis, et al. (1997) uses bicycle perspectives in real-time to identify important quality of bicycle service factors to develop a bicycle level of service (LOS) formula for assessing infrastructure. According to Landis et al., readily identifiable bicycle LOS would facilitate setting priorities for bicycle facility construction projects, since "the choice between bicycle-facility projects is often made in the absence of an objective supply-side evaluation of the existing roadway facilities". The study placed participants in actual traffic situations, gathering real-time feedback about user perceptions to inform traffic stress criteria. Researchers then developed a model incorporating traffic volume and speed, traffic mix, potential cross-traffic generation, pavement surface condition, and width of bicycle allowance (Landis et al., 1997). However, according to Mekuria et al. much of this data is not readily available, and the study's calculations generate level of service ratings that come from black box formulas and "have no meaning either to roadway managers or to the general public…" (Mekuria et al., 2012). Because many level of service studies rely on data that is unavailable, it is important to develop a metric that can be used based on data that cities already collect.

In another study, Carter et al. (2007) developed an intersection safety index based on videorecorded bicycle-motorist conflicts and avoidance maneuvers at several intersections in four major U.S. cities. The intersection safety index accounts for traffic volumes and speed limits on both intersection streets, the numbers of lanes, presence of a bicycle lane, presence of on-street parking, the number of right turn lanes, the presence of a traffic signal at the intersection, and the turning behavior of vehicles (Carter et al., 2007). The intersection safety index presents a viable data source for needed improvements; however, the researchers acknowledge that the index is based upon the number of interactions between bicyclists and motor vehicles, and that a high number of interactions is not necessarily unsafe, though they may create a perception of riskiness for bicyclists (Carter et al., 2007).

Network connectivity and continuity

Mekuria et al. discuss how low-stress facilities in San José's bicycle network are disjointed due to arterial streets. Their research observes how arterial streets designed for moving automobiles through the city at high speeds interrupts low-stress bicycle corridors, rendering them insufficient as a network for cyclists with lower stress tolerances (Mekuria et al., 2012). Other researchers have identified areas in which bicycle facilities simply dead-end without warning, leaving cyclists stranded (*10*). This study, based in Minneapolis, Minnesota, assesses cyclists' responses to bicycle lane discontinuity (i.e. bicycle lanes becoming displaced at intersections by vehicle right-turn lanes, Class II bicycle lanes ending and becoming Class III facilities, etc).

Factors affecting user comfort level

A variety of research has supported the hypothesis that bicycle-specific facilities enhance the perception of safety in cycling, with wider facilities being most effective. A King County, Washington study conducted by Moudon et al. (2005) using cycling behavior data and parcel-level GIS land use designations found that specific features of the built environment, namely proximity to trails and bike lanes, and "presence of agglomerations of offices, clinics/hospitals, and fast food restaurants, measured objectively, are significant environmental variables" in determining of the likelihood of cycling. This study suggests that the type of land use and type of facility contribute to the comfort as well as convenience of cycling for transportation (Moudon et al., 2005). Parker et al. found an increase in cycling in a diverse New Orleans neighborhood after the addition of bicycle lanes along two adjacent streets. The study measured bicycle ridership before and after the lane restriping, taking ridership counts on the adjacent streets restriped to include bicycle lanes, as well as the other adjacent streets in the area, to distinguish between changes in rider behavior and new ridership (Parker, 2013). That ridership increased with addition of bicycle lane striping further confirms the importance of infrastructure to road users, especially bicyclists.

Lane width, motor vehicle speed, visibility at intersections, presence of intersections, and street shading were deemed the most important roadway attributes in determining roadway suitability for cycling among survey respondents in medium-sized cities in urban Brazil (Providelo and Sanches, 2011). These attributes were ranked highest in importance by survey respondents, from a pool of fourteen attributes gathered through focus group studies. The remaining attributes available for survey selection, identified by focus group participants, were: motor vehicle volume, signalization at intersections, presence of heavy vehicles, direction of traffic flow, pavement condition, driveways and side-streets, on-street vehicle parking, roundabouts, and grades (slope steepness) (Providelo and Sanches, 2011). In another stated preference survey, Sener et al. (2009) found that individuals were willing to pay, in terms of extra time spent commuting, to avoid a high number of stop signs, red lights, and on-street parking. With the presence of on-street parking, individuals were interested in avoiding high-turnover parking, parallel parking, and areas with long stretches of on-street parking adjacent to bicycle facilities (Sener et al., 2009). The results that consistently stood out in importance among the rest reflect attributes can be more heavily focused on from a planning perspective to improve built environments for bicycle use.

Tilahun et al. also developed an adaptive stated preference survey to rank bicycle facilities, using video simulations of various roadway conditions to determine the value, in terms of additional time spent commuting, participants assigned to various bicycle facility features. The study found bike lane improvement to be the most important feature participants would pay additional commuting time to obtain, ranked above parking elimination or off-road improvements alone (Tilahun, 2006). In another analysis of 35 U.S. cities, Dill et al. found that "higher levels of bicycle infrastructure are positively and significantly correlated with higher rates of bicycle commuting" (Dill et al., 2003). These studies imply that infrastructural improvements have a high potential to enable large gains in ridership.

In a report from the Portland Office of Transportation, Roger Geller points out that "no person should have to be 'brave' to ride a bicycle". In discussing user preferences, he identifies four distinct cyclist types ("strong and fearless", or those who would be cycling even if no improvements were made; "enthused and confident", or those made interested by Portland's efforts to improve cycling in the city; "interested but concerned", or those interested in cycling for recreation or transportation but concerned about safety; and "no way no how", or those disinterested in cycling regardless of potential facility improvements), which this study uses for reference in its traffic stress level analysis (Geller, n.d.). Geller points out that the need for improvement is evidenced by numbers: the "interested but concerned" group typically makes up the largest portion of most urban populations in the United States (Geller, n.d.).

Synthesis

Existing bicycle research delves extensively into the relationship between bicycling and land use and provides valuable insight about bicyclists' preferences. Both planners and researchers recognize the importance of understanding the types of features cyclists prefer to have nearby, as well as what cyclists may go out of their way to avoid. This recognition is further demonstrated through current research about bicycle needs. The literature also references a need for more accurate performance measurement for evaluating bicycle facilities, which this study aspires to provide for San Diego.

Methodology

Research Design

In this study, I quantify the San Diego region's bicycle facilities through analysis of spatial datasets of bicycle infrastructure provided by the San Diego Geographic Information Source (SanGIS). The geographic information systems (GIS) software allows categorization and quantification of spatial data, so that existing bicycle routes may be modified to account for the external factors that influence their comfort levels to users.

This study is primarily modeled after Mekuria et. al.'s 2012 analysis, which generated a bicycle facility network map for each level of traffic stress. The LTS 1 map (the lowest level of traffic stress) generated by the Mekuria study showed several intraconnected areas of low traffic stress which were disconnected from one another, demonstrating that individuals interested in traveling by bicycle without encountering substantial traffic stress currently do not have mobility options beyond individual neighborhoods and residential areas.

Field site

I chose the San Diego region as a research location because its year-round temperate weather, culture of outdoor activity, and high congestion during peak-hour traffic make it a prime location for bicycle use as a method of transportation. Although infrastructure conditions may currently make the region an undesirable choice for bicycle use as a method of transportation, residents may likely be interested in bicycling for transportation provided appropriate infrastructure, since there are currently more San Diegans who cycle for utilitarian than recreational reasons (City of San Diego, 2013). Due to San Diego's mild climate and thriving outdoor community, it is likely that road and traffic conditions serve as more of a deterrent to bicycling than do weather and culture in the region. This presents planners and decision makers an opportunity to increase cycling simply through improving infrastructure.

Levels of Traffic Stress

This study uses the LTS criteria established by Mekuria et al., with influence from Roger Geller's "Four Types of Cyclists", to determine LTS thresholds for measuring San Diego's bicycle network. Specific components of how the categories are quantified are discussed in Table 2

Data Analysis

The study will assign a level of traffic stress to every section of road and bicycle path in San Diego using the following characteristics.

Roadway speed

Roger Geller (n.d.), Providelo and Sanches (2011), the AAA Foundation (2011), and Mekuria et al. (2012) note traffic speed as the among the most important determinants for bicycle use, safety, and comfort levels. This study will add information about adjacent roadway speeds to appropriate bicycle facilities and use the information to help determine traffic stress levels.

Bike lane and path grades

Bicyclists have varying levels of fitness and bicycle handling skill, and steep grades may pose stress or challenges to some cyclists. San Diego is a geographically diverse area with many canyons and mountains, and its roads and bicycle facilities follow the existing topography. While physically fit cyclists may brave steep grades during commutes, or even seek them out for recreation or exercise, many individuals cycling for transportation or light exercise may in fact avoid these facilities.

Bicycle facility type

While extreme differences may exist among facilities of the same type (as discussed throughout this report), bicycle facility types are inherently different from one another and, cause inherent differences in traffic stress levels (Mekuria et al., 2012; Geller, n.d.). Bicycle facility types are therefore included in this study; the relationship between bicycle facility type and LTS is discussed in Table 2.

Origin, form, and purpose of data

This study extracts useful metrics from existing bicycle and traffic data and to create mobility corridor information, analyzing the current transportation system for bicycle accessibility. This report primarily uses spatial obtained from SanGIS through its Regional Data Warehouse, which provides public access to spatial data pertaining to the County of San Diego. Metadata and applicable tables pertaining to the data used are available upon request.

The shapefiles used in this study were selected based on their ability to provide spatial data about roadway attributes within San Diego County and are described in Table 1.

Assigning Levels of Traffic Stress

In order to assign traffic stress levels based on specific attributes, the data below were loaded into an ArcGIS map document, and then combined into one shapefile corresponding to bicycle infrastructure data. Each characteristic was allocated a contribution to bicycle level of traffic stress (LTS) based on user preference data gathered in previous studies. LTS values based on facility and traffic characteristics are shown in Table 2. The LTS values for each roadway characteristic were assessed and then combined into an overall traffic stress classification using a weakest link methodology; in this way, each road segment received a LTS equal to the greatest contributing LTS. For example, a light collector street (LTS 2) with an over 50% slope (LTS 4) would be rated LTS 4. A bicycle lane (LTS 2) adjacent to 35-mph traffic would receive an LTS rating of at least 3, depending on the other characteristics of the roadway.

Creating the Origin-Destination Matrix

The ArcGIS software provides a network analysis tool that allows line shapefiles to be converted into transportation networks for travel analysis. The Network Analyst tool can provide shortest-path route analysis, find facilities within a certain radius, or create origin-destination matrices.

For this analysis, the LTS network was separated into four shapefiles the destinations available along certain traffic stress level networks would be located without traveling along higher stress facilities. Each LTS shapefile included lower stress facilities, since an individual traveling by bicycle and comfortable cycling on LTS 3 facilities would also ride LTS 1 and LTS 2 facilities. Thus, the shapefiles were divided into (1) LTS 1; (2) LTS 1 and 2; (3) LTS 1, 2, and 3; and (4) LTS 1, 2, 3, and 4.

The next step was to create a Network Dataset for each traffic stress network. ArcGIS provides several configuration options for Network Dataset creation. In this case, no additional constraints were selected, as traffic stress levels were already built into the analysis by being located in separate files. The analysis settings selected for this study are included in a separate appendix.

Table 1: Shapefiles used in study

Name	Contents	Source	Date	Extent	Feature Type	Number of Records	Data Used in Study
“Roads_ All”	Centerline segments for roads (active, inactive, public, private, constructed, or unconstructed)	Data received from all official jurisdictions within San Diego County.	5/4/15	Spatial: San Diego County	Line	157,914	• Road name • Speed (average driving speed established by emergency vehicle dispatch agencies) • Functional Class (i.e. freeway; local; etc.)[1] • Segment length
“BIKE_ ROUTES”	Existing bicycle facilities in the San Diego Region, based on the “Roads_All” layer	SANDAG, using input from local jurisdictions.	4/10/15	San Diego Region	Line	15,815	• Route (type of facility) • Segment length
“Slopes_ CN”	Aggregated slopes for San Diego County using Interferometric Synthetic Aperture Radar (IfSAR) elevation surfaces of the County.	County of San Diego Land Use and Environmental Group GIS Service	1/1/05	San Diego County	Polygon	367,820	• Percent slope grade in four aggregated categories: -Less than 15% slope -15% to 25% slope -25% to 50% slope -Slope 50% or greater
“PLACES”	Point layer showing location of areas and specific features including businesses and outdoor features.	County of San Diego, SANDAG, San Diego County Sheriff, US Board on Geographic Names	4/25/13	San Diego County	Point	28,580	• Facility name • Address • Type of facility

[1] A list of all functional classes and their associated traffic stress levels is provided in Table 2.

Table 2: Level of Traffic Stress Calculation by Road Attribute

	Criteria	LTS
Speed	0-25 mph	1
	26-34	2
	35-45	3
	46+	4
Bicycle Facility	No designation[2]:	
	-Local Road with speed < 25mph	1
	-Private Road with speed<25mph	1
	-Unpaved road with speed<50mph	1
	-Recreational Parkway	1
	-Pedestrian/Bikeway	1
	-Military with speed<25mph	1
	-All others	2
	Class 1 – bike path	1
	Class 2 – bike lane	2
	Class 3 – bike route	2
	Multi-Use Path	1
	8: Other suggested Routes	2
	15: Bikeways coming soon	6 (non-existent)
	6: Freeway Shoulder with bike access	4
Road type	1...Freeway to freeway ramp	5 (prohibited unless “Bike_LTS” > 0 and < 4)
	2...Light (2-lane) collector street	2
	3...Rural collector road	3
	4...Major road/4-lane major road	3
	5...Rural light collector/local road	2
	6...Prime (primary) arterial	3
	7...Private street	1
	8...Recreational parkway	1
	9...Rural mountain road	3
	A...Alley	2
	B...Class I bicycle path	1
	C...Collector/4-lane collector street	3
	D...Two-lane major street	2
	E...Expressway	5 (prohibited unless “Bike_LTS” > 0 and < 4)
	F...Freeway	5 (prohibited unless “Bike_LTS” > 0 and < 4)
	L...Local street/cul-de-sac	1
	M...Military street within base	1
	P...Paper street	6 (prohibited)
	Q...Undocumented	n/a
	R...Freeway/expressway on/off ramp	5 (prohibited unless “Bike_LTS” > 0 and < 4)
	S...Six-lane major street	4
	T...Transitway	1
	U...Unpaved road	1
	W...Pedestrianway/bikeway	1
Slope	0-15%	1
	15%-25%	2
	25%-50%	3
	>50%	4

[2]The “Roads_All” network contains more records than the “BIKE_ROUTES” network. For features with no bicycle facility designation, road criteria were used to determine the bicycle level of traffic stress. This allows accounting for facilities such as local roads, which studies have shown produce low traffic stress for bicycles.

Finally, I imported each Network Dataset and a set of Origins and Destinations into the Origin/Destination Matrix under the Network Analyst tool. In this case, I used the “POINTS” shapefile described above as the origins and destinations for the analysis for each traffic stress network, in order to ensure an equal comparison. When importing the origins and destinations into the Origin/Destination Matrix tool, I set a search tolerance for 200 feet – this would be the maximum distance a destination or origin could deviate from the bicycle network and still be analyzed for routes in the matrix. Each bicycle network origin/destination analysis was conducted with a trip distance limit of 5 miles. Thus, all trips identified under each origin/destination matrix for each level of traffic stress would obey the following rules:

- Locate only the origins/destinations that are within 200 feet of the bicycle network
- Locate only the routes between origins/destinations that use bicycle facilities at or below the threshold traffic stress level
- Routes may only be up to five miles long

Findings

As described in the Methodology section, I set out in this study to produce three products:

1. A bicycle level of traffic stress (LTS) map for the San Diego region
2. An origin-destination matrix for each LTS network illustrating its connectivity
3. A comparison between bicycle demand for the region and traffic stress levels

The sections below reveal the findings of this research with respect to these products.

Bicycle Level of Traffic Stress Map for San Diego Region

Figure 1 shows the network for each traffic stress level for particular areas in the San Diego region. Although at first glance it appears as though the entire region is populated with Traffic Stress Level 1 facilities, a close look at the LTS 1 network in the top left reveals the disconnections between LTS 1 bikeways.

The disconnections between LTS 1 facilities in La Jolla are characteristic of the bicycle network throughout the region. Local, low-speed streets are interconnected by collector and arterial streets and interrupted by freeways and natural features.

Origin-Destination Matrices for Traffic Stress Levels

Table 3 lists the number of possible origin/destination connections for each traffic stress level within a five-mile radius. Only one route is calculated for each origin/destination pair. Where two facilities may be connected by more than one route, only the shortest path is counted in the number of routes. The same set of locations is used for both “origins” and “destinations” in the network origin/destination matrix.

Table 3: Origin/Destination Results for each LTS

	LTS 1	LTS 1-2	LTS 1-3	LTS 1-4
Unlocated Origins	13,647	11,088	6,013	5,255
Unlocated Destinations	13,647	11,088	6,013	5,255
Origin/Destination connections available	264,451	1,267,295	19,530,570	22,758,325

Figure 2 illustrates the routes available for each traffic stress level network in San Diego County, based on origins and destinations provided by the “PLACES” data layer. Each straight line represents an origin-destination connected route.

Figure 1: LTS Networks 1, 2, 3, and 4 (left to right top, then bottom)

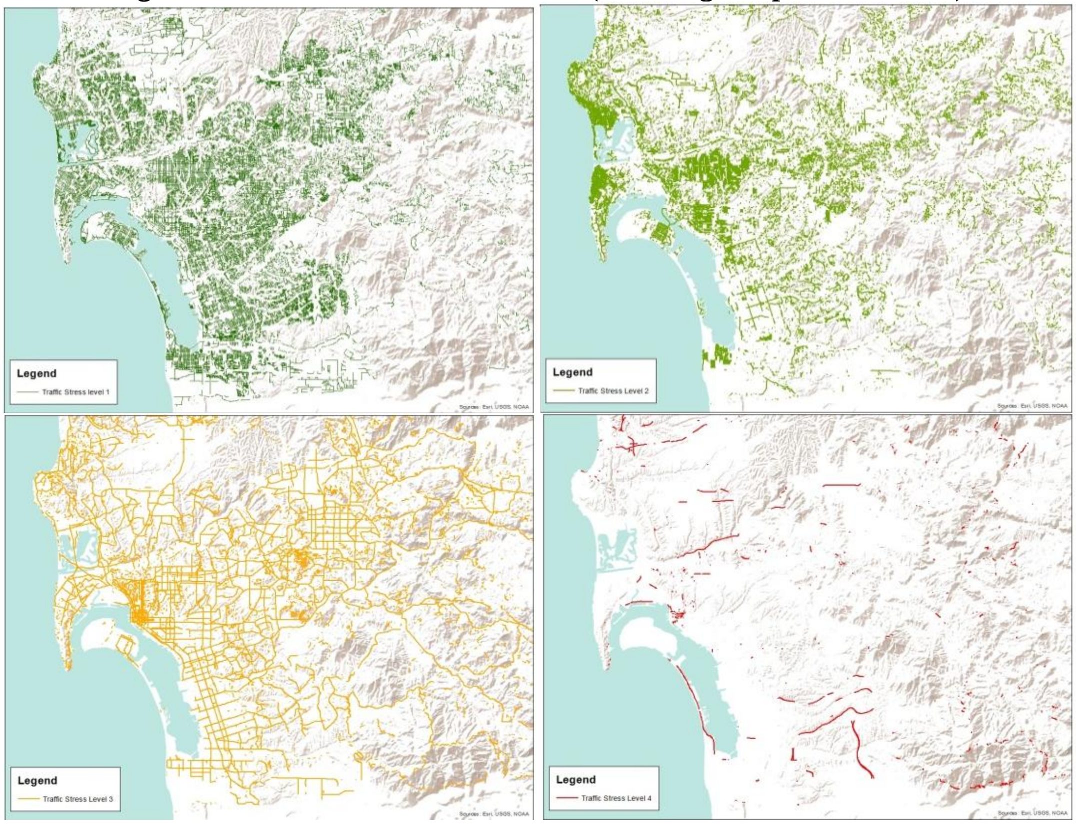
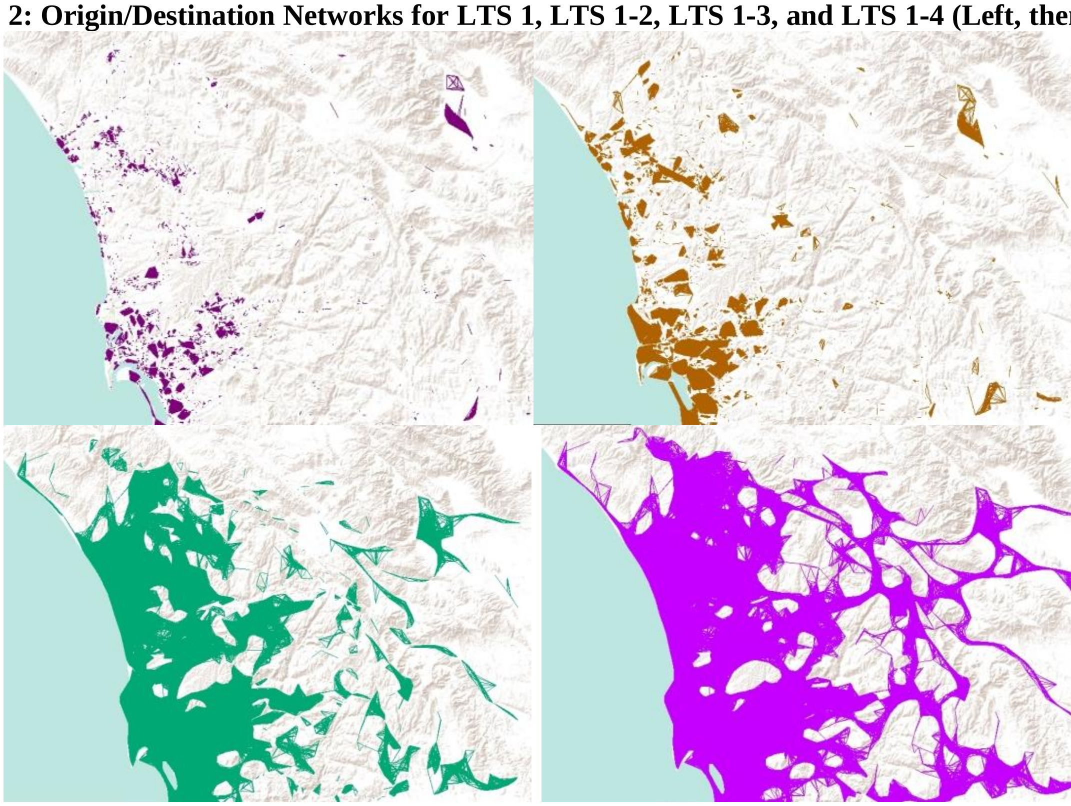


Figure 2: Origin/Destination Networks for LTS 1, LTS 1-2, LTS 1-3, and LTS 1-4 (Left, then Down)

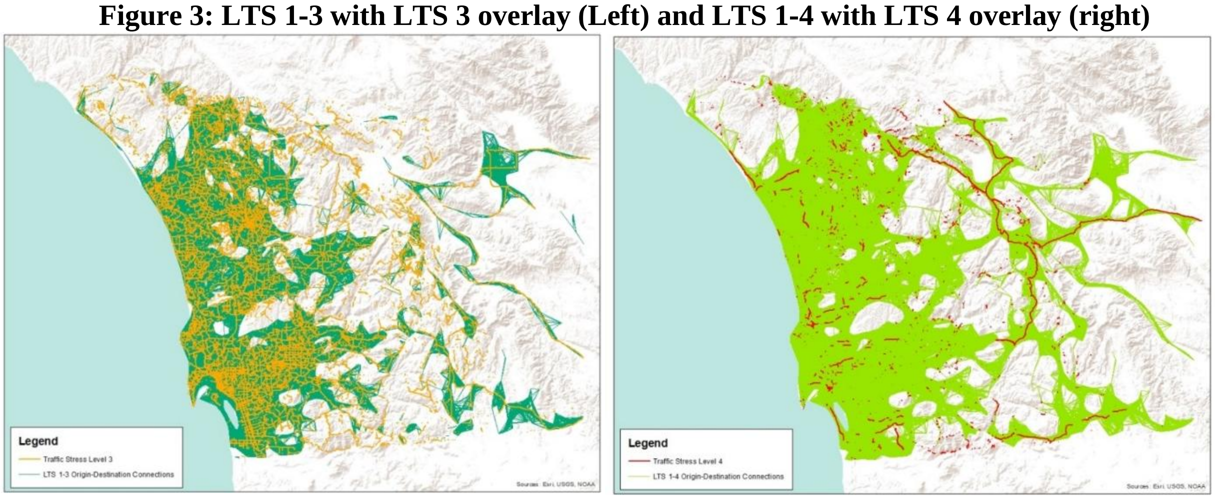


Discussion

The figures above provide an overall picture of the bicycling experience in San Diego County. They demonstrate that lower stress bicycle facilities tend to cluster in metropolitan and residential areas, while unincorporated and rural areas tend to be predominated by higher stress facilities. LTS 1 facilities tend to provide connectivity at the most basic level, while LTS 2 and 3 facilities provide routes between these areas. This is a logical result of the common municipal street structure: small, low-speed local roads make up our neighborhoods, and larger, higher-speed (and higher-stress) arterial roads connect the neighborhoods. The LTS 1 network in Figure 2 provides a clear example of this, illustrating clusters of LTS 1 facilities with no low-stress facilities to connect them. The origin-destination matrices illustrate the exponential gains in mobility a person on a bicycle may achieve simply by increasing his or her tolerance for traffic stress.

In Figure 3, I added an overlay of the LTS 3 road network to the LTS 1-3 origin-destination matrix (left) and an overlay of the LTS 4 road network to the LTS 1-4 origin-destination matrix (right). The LTS 1-3 matrix accounts for destinations available using the LTS 1, 2, and 3 networks. Adding the 3,674 miles of the LTS 3 roadway network allows access to over 18 million more destinations than are reachable the LTS 1-2 network alone. The LTS 1-4 matrix on the right of Figure 3 illustrates the increased accessibility gained from expanding into the traffic stress level 4 network. Adding the 411 miles of the LTS 4 network allows connection to over three million destinations that could not be reached through LTS 1-3 alone.

Figure 3: LTS 1-3 with LTS 3 overlay (Left) and LTS 1-4 with LTS 4 overlay (right)



Significance of Findings

This study provides three main outputs: a more detailed picture of San Diego's bicycle network, a close look at the mobility provided by each level of the network, and a methodology for providing a bicycle stress network.

Interruptions along bicycle routes, which are commonly encountered, are often met through braving higher-severity traffic conditions or accepting a longer detour to arrive at one's destination, these route interruptions serve as a deterrent for many from using a bicycle for transportation or even recreation. Understanding what contributes to traffic stress for individuals on bicycles, and including these factors in the bicycle network, provides a much clearer picture of what facilities are actually available for travel.

Limitations of this Study

<u>Excluded data</u>

The main limitation of this study is that it does not account for some of the variables studies have shown to be the largest influences of cyclists' levels of traffic stress. These variables were omitted due to lack of available data and include pavement quality, traffic volumes and road widths (although road type helps account for these), bicycle facility widths, roadway shoulders, street parking and turnover, unrestricted right-turn lanes, median widths, and lighting.

In addition, the lack of sufficient data about bicycle paths – namely their widths and pavement quality – cause this study to treat all bicycle paths as equal facilities but for slope steepness, when in fact bicycle paths can vary widely in LTS due to path width and pavement quality, as well as a number of factors including lighting, nearby crime rates, and vegetation encroaching into the cycling space.

Data integrity of point locations

SanGIS's "PLACES" data layer provides a useful mechanism for examining a range of possible origins and destinations that included a variety of land use types, as well as a set of locations geographically dispersed throughout the San Diego Region. However, because the data is combined from an assortment of GIS layer types for a variety of intended uses, some of the data points are not truly potential destinations available to an individual riding a bicycle. For example, the dataset contains "harbor" and "extractive industrial" land use types that are in some instances plotted by ArcGIS as located in the Pacific Ocean.

Limitations of Origin-Destination Matrix Model

While "PLACES" data points located in the Pacific Ocean ordinarily would be too far from the LTS network to be captured by any routes, the San Diego – Coronado ferry is classified as a facility (LTS 1) under the bicycle network. Data points within 200 feet of the Coronado Ferry route were included as viable travel destinations and factored into the origin-destination matrix. However, the ferry is the only non-bicycle route included in the network analysts, and the number of additional destinations captured is negligible.

The number of trips identified for each traffic stress level is a fraction of trips available for the region since not all possible destinations are captured in the "PLACES" layer, and since the trips are capped at a five-mile length and do not account for inclusion of other modes of travel. The model is not intended to illustrate the total number of trips possible, but instead to provide a comparison between the mobility levels of each traffic stress network for short trips, and to illustrate the relative mobility gains yielded by expanding into a higher stress network.

Intersections

Mekuria et al. pointed out that when a low traffic stress facility crosses a higher stress facility, individuals with a low tolerance for traffic stress may be deterred from even crossing the intersection, diminishing the number of trips available. The San José study conducted by Mekuria et al. accounts for this by excluding higher stress facility crossings from the available trips in their traffic stress model. In this study, such interruptions are not counted as barring potential trips because employing this capability would require modeling and data manipulation that were not feasible under the scope of this study. Therefore, higher stress crossings do not "interrupt" a lower stress facility in this study.

Conclusion

The San Diego region presents ample opportunities for recreational and transportation cycling through its year-round temperate climate and its active culture. While jurisdictions within the region express the importance of providing quality facilities to increase cycling, performance is usually measured based on the facility type, which does not account for other factors that influence whether the facilities are used. This research demonstrates that roadway attributes can be used to generate maps that provide a greater picture of the bicycling experience for an area.

Intuitively, based on traffic speed, bicycle facility type, and slope grade, the current system provides the greatest mobility to the bravest cyclists. However, this study's findings provide San Diego planners the opportunity to develop measures that help provide equitable facilities for all individuals riding bicycles. With development of a low-stress network that provides adequate mobility to each user type, San Diego has the potential to meet its goals of improving cycling as a viable mode of transportation, and increasing the number of cycling trips throughout the region.

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