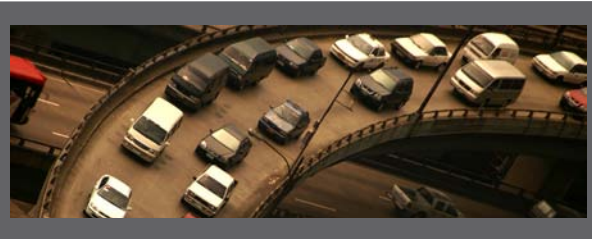


Low-Stress Bicycling and Network Connectivity



MTI Report 11-19



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REPORT 11-19

LOW-STRESS BICYCLING AND NETWORK CONNECTIVITY

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EXECUTIVE SUMMARY

CLASSIFYING STREETS AND CROSSINGS BY LEVEL OF TRAFFIC STRESS

A city or region's bicycling network can be variously defined as its inventory of bicycling facilities, or as the links that cyclists are permitted to use. However, considering the many Americans who don't ride a bike regularly because of the lack of safe routes to ride, a third way of defining the bicycling network is the set of streets and paths that do not exceed people's tolerance for traffic stress.

Past research has demonstrated that Americans have varying levels of tolerance for traffic stress, which is a combination of perceived danger and other stressors (e.g., noise, exhaust fumes) associated with riding a bike close to motor traffic. While a small fraction of the population will tolerate sharing a road with heavy or fast traffic, a large majority is "traffic-intolerant," willing to tolerate only a small degree of traffic stress. According to one popular scheme for classifying riders, the traffic-intolerant majority is called "interested but concerned," in contrast to the "enthused and confident" and the "strong and fearless," smaller groups that will tolerate greater levels of stress.

In the U.S., researchers have developed a few schemes to classify streets according to the stress they impose on cyclists (or, conversely, the level of comfort cyclists feel), the best known being the Bicycle Level of Service (BLOS), in which streets are graded from A to F, like the level of service for motor traffic. While this method could in principle be used to rate streets, it has some practical shortcomings. One is that it requires traffic volume and lane-width data that is generally unavailable. A second is that there is no clear correspondence between BLOS level and user tolerance; that is, the method makes no attempt to establish a particular level of service as the minimum required to serve the mainstream population. In European countries with high levels of bicycle use, national standards describe the kind of separation from traffic that is expected in order to serve the mainstream, traffic-intolerant population.

This research proposes a new scheme for classifying road segments by one of four levels of traffic stress. Level of traffic stress 1 (LTS 1) is meant to be a level that most children can tolerate; LTS 2, the level that will be tolerated by the mainstream adult population; LTS 3, the level tolerated by American cyclists who are "enthused and confident" but still prefer having their own dedicated space for riding; and LTS 4, a level tolerated only by those characterized as "strong and fearless."

Criteria are proposed for classifying road segments by level of traffic stress depending on traffic characteristics (e.g., road width, traffic speed, the presence of a parking lane) and whether bikes are in mixed traffic, in bike lanes, or on segregated paths. A low level of stress can be achieved in mixed traffic on local streets with low traffic speeds. As the number of lanes, traffic speed and traffic volume increase, providing a low level of stress requires progressively more protective measures – dedicated bike lanes and, ultimately, physically segregated bikeways.

Criteria for LTS 2 are based on Dutch bicycle facility planning and design standards. The Dutch norms have proven to attract a large percentage of the population to cycling (80 percent of the population rides at least once a week), including high participation rates among women and seniors. Criteria for the other levels of traffic stress require either more separation from traffic (for LTS 1) or progressively less (for LTS 3 and 4).

Similar criteria were developed for classifying intersection approaches and unsignalized crossings. Criteria for intersection approaches deal with the conflict between through bikes and right-turning traffic.

While the network analysis principles demonstrated in this research use the newly proposed classification scheme, they can equally be used with other classification schemes.

ISLANDS AND BARRIERS IN BICYCLING NETWORKS LIMITED TO LOWER-STRESS LINKS

For that segment of the population that will tolerate only streets with a certain level of traffic stress – say, LTS 2 – their bicycle network is taken to be the subset of the street and path network whose links have LTS 2 or less. As a corollary of this assumption, the stress of a route is determined by its most stressful link, not by an average. Several low-stress links cannot compensate for a high-stress link.

Using San José, California, as a case study, every segment (block) of its street and path network was classified by level of traffic stress. Stress maps show that while 64 percent of the network consists of links with the lowest level of stress (mainly residential streets), those low-stress links are poorly connected. This is not a coincidence; in urban planning, streets are often laid out so as to prevent through traffic from using local streets. Thus, in spite of the existence of a large mass of low-stress links, it is often impossible to get “from here to there” without being forced to use higher-stress links. Maps including only links with LTS 1 or 2 reveal many gaps created by barriers. Because of these barriers, the city is composed of many “islands of low-stress connectivity” – that is, areas within which one can find a low-stress route, but requiring the use of high-stress links to get from one island to another. Some of these islands are rather large (thanks to the city’s bike-planning efforts), but many are very small.

Barriers to low-stress connectivity have three general types. One is natural and man-made barriers that require grade-separated crossings such as freeways, railroads, and creeks, whose crossings tend to be widely spaced and are often adapted to high traffic volumes and therefore carry high stress. A second is arterial streets whose cross streets lack the combination of a low-stress approach *and* a safe crossing. Often, the only safe crossing provisions are at traffic signals, where the cross streets themselves have high stress, often because of turning lanes that are added on the intersection approaches. A third kind of barrier is breaks in the neighborhood street grid, a common feature of newer developments that force traffic, including bicycle traffic, to use arterials to access the local streets.

MEASURING CONNECTIVITY

Two points are said to be connected at a given level of traffic stress if there is a path between them using only links that do not exceed the given level of stress that does not involve undue detour. The detour criterion used was that the length of the lower-stress path should not exceed the length of the most direct route by more than 25 percent or, for short trips, 0.33 miles.

For evaluating the connectivity of a city or regional network for a specified level of traffic stress, two measures are proposed. “Percent trips connected” is the percentage of trips in the regional trip table that are connected without exceeding the specified level of stress and without undue detour. “Percent nodes connected” is the percentage of node-to-node pairs in the street network that are connected without exceeding the specified level of stress and without undue detour. Because bicycling tends to be a valid alternative mode only for trips within a certain distance range, these percentages can be applied to only those trips or node-to-node pairs that are not too long (e.g., not more than six miles) or too short (e.g., not less than 0.5 miles).

Regional trip tables use traffic analysis zones (TAZs) as their geographic unit of demand. This zone size is shown to be too coarse for modeling access to the bicycling network, because there are often barriers within a TAZ that allow part of the zone to have low-stress access to an attractive bike route while the rest of the zone doesn’t. We propose therefore using census blocks as geographic units of demand. We developed and demonstrate a method of disaggregating zonal demand for work trips to the block level. Trip origins are distributed in proportion to block population, while trip destinations are distributed in proportion to a block’s “attraction strength,” which is the sum of the attraction strength of the parcels that make up the block. Attraction strength for a parcel, in turn, is the product of the parcel size and a trip generation coefficient based on zoning that reflects the likely intensity of non-residential development. Thus, for example, the trip generation coefficient increases as land-use goes from low-density housing to high-density housing to retail to office.

With demand thus estimated at the block level, “percent trips connected” is determined by summing the demand over all connected block pairs, and expressing that as a ratio to total demand. To limit the influence of very short trips for which walking is the most likely mode of travel, trips whose origin and destination are in the same traffic analysis zone are excluded from the calculation. For San José, for trips up to four miles in length, the number of trips connected at LTS 1 (suitable for children) was only 0.7 percent. At LTS 2 (tolerable to the mainstream adult population) and for trips up to six miles long, it was only 4.7 percent. This sounds like bad news; however, it can also be taken as good news in the sense that it shows a large potential for increasing bicycling’s share of the travel market by increasing low-stress connectivity.

EXAMPLE APPLICATION

To illustrate the power of having a measure of connectivity, a slate of network improvements was proposed. Amounting to 32 miles and spread over 16 corridors, it consists mainly of

small projects, such as improving the safety of a crossing or of an intersection approach or providing a short section of connecting path. The slate also includes two long projects along corridors that lack an easily completed route that mainly uses smaller streets. With this modest set of improvements, percent trips connected at both LTS 1 and LTS 2 improve by a factor of 2.5. This case study illustrates the power of the proposed connectivity measures to characterize a benefit that is well understood by planners but previously has not been measurable. It also illustrates how a modest set of network improvements can leverage the large mass of existing low-stress links by closing gaps, creating a connected web.

Readers are encouraged to peruse the report's figures, many of which are maps that illustrate connectivity concepts better than can be done using words.

I. INTRODUCTION

This introduction describes the study's objectives and gives a road map to the remaining sections of the report.

OBJECTIVE 1: A USER-ORIENTED BICYCLING NETWORK DEFINITION

In one sense, a city's or region's bicycling network is all of its roads and paths on which bicycling is permitted. However, some streets provide such a poor level of safety and comfort for bicycling that the majority of the population considers them unsuitable for bicycling.

To make bicycling safer and more appealing, cities often make bicycle-related improvements to certain streets. They include bike lanes, shared lane arrows ("sharrows"), segregated bike paths or shared-use paths, signs indicating that a street is a bike route, traffic diversion devices to reduce through motor traffic while permitting through bike traffic, and traffic calming devices such as speed-cushions and neighborhood traffic circles. Because these improvements have been designed and installed by a city's public works department (or equivalent), and have to be maintained by the city, it is natural that these facilities be inventoried. This inventory is often considered as a city's bicycling network.

However, this "inventory definition" can deviate substantially from the network of paths and streets people deem safe enough to use. It will exclude many streets that have no bicycle-related improvements yet are perfectly suitable for bicycling by virtue of having low traffic speeds and volumes. It may also include "improved" streets that still subject cyclists to more traffic stress than most people are willing to accept. Examples include designated shared lanes on streets with traffic speeds of 30 mph or more, bike lanes in commercial areas where double parking and other commercial activities routinely force cyclists to merge into the travel lane, bike lanes on high-speed roads (Figure 1), and bike lanes that disappear on intersection approaches when the right travel lane becomes a right-turn lane (Figure 2).



Figure 1. Bike Lane on a 40-mph-Speed-Limit Road



Figure 2. Bike Lane Disappears to Make Space for a Right-turn Lane

A third way to define a bicycling network, which might be called the normative definition, is the set of streets and paths that bicyclists are expected or advised to use as primary routes. It will include attractive, low-stress links, but in many American cities, it will also include links that carry high stress but are still the best bicycling route available in a given corridor. The result may well represent where people actually ride, but it fails to account for the large numbers of would-be cyclists who don't ride because they do not perceive a safe route available to them.

The idea is that most cyclist trips will follow links on this network, using other streets and paths only to access the “network” or for short local trips. With such a normative definition, the network will of necessity be well connected.

The first objective of this study is to propose and test the practicality of a fourth way of defining the bicycling network: as the set of streets and paths that people consider acceptably safe for bicycling. This stress-based definition can result in a fragmented, disconnected network. With a network so defined, it may indeed be impossible to get “from here to there.”

Recognizing that people differ in their tolerance for traffic stress, our methodology divides the population into four classes based on their level of traffic tolerance, with group 1 the least tolerant and group 4 the most tolerant. It then proposes a corresponding classification scheme for links in the bicycling network, classifying them according to whether the traffic stress they impose on cyclists would be tolerated by cyclists in group 1, 2, 3 or 4. Sections II-V describe the four levels of traffic stress and the criteria proposed for assigning levels of stress to links, intersection approaches, and crossings. Those definitions were then applied to all of the streets in San José, the case study used as a proof-of-concept for the proposed methodology.

Consistent with this logic, the bike network available for people with any given level of tolerance for traffic stress is a subset of that available to people with a higher tolerance level. People who tolerate up to stress level 3, for example, can use all links whose stress level is 3 or lower, while those who tolerate up to stress level 2 can only use links whose stress level is 2 or lower. This logic also implies that the “weakest link” principle governs when aggregating over links that form a possible route. That is, the stress of a route is determined by its most stressful link, and not by the sum or average of the stress on its constituent links. If people will not use links whose stress exceeds their tolerance, several low-stress links cannot compensate for one high-stress link.

OBJECTIVE 2: A NETWORK CONNECTIVITY METRIC

In contrast to a normatively defined network, the user-perspective-based network may be incoherent – that is, it has some areas not connected to others. Lack of connectivity is not a necessary characteristic of a bicycling network based on user tolerance, but it is unfortunately a real characteristic of bicycling networks in many American cities, where many people find it impossible to get to where they want to go by bike without riding on links with unacceptably high traffic stress.

Connectivity is perhaps the most critical aspect of a bicycling network and should feature prominently in network planning. Network analyses for automobile and transit modes take connectivity for granted and focus on more advanced issues, such as travel time and congestion. However, for bicycling, lack of connectivity is critical with respect to potential and actual bicycle use. Most bicycling in the U.S. is discretionary, and if people can't get to their destinations on a safe, low-stress bike route, most of them will use a different mode of travel. Planners understand this, and network improvements are often proposed based on the connectivity they will provide; however, planners lack a quantifiable measure of connectivity that might be used to justify an improvement.

Thus, the second objective of this project was to develop metrics for low-stress connectivity, or the ability of a network to connect travelers' origins to their destinations without subjecting them to unacceptably stressful links.

Two points in a network may be connected, but the route connecting them may be so circuitous that most people would consider them effectively unconnected and would feel obligated to take a shorter, higher-stress (and therefore unacceptable) route. To account for this, the proposed methodology requires defining an acceptable level of a detour. The definition of connectivity for a pair of points is then expanded to mean *the ability to get between the two points without exceeding a specified stress threshold and without exceeding the specified level of detour.*

For bicycling networks, connectivity at an acceptable level of traffic stress and without undue detour is the most fundamental measure that determines how well a network serves the community. While there are many factors that influence bicycle use that are beyond the control of government policy – weather, for example – the main determinant that can be directly controlled by government planning and engineering is how many people have an acceptable route from their origin (e.g., their home) to their destination (e.g., work, school, store, etc.). The number of miles of bike lane or bike path in a city can be a misleading statistic unless those facilities genuinely offer a low-stress bicycling environment, and unless they are linked together in a coherent network that provides relatively direct access between people's homes and destinations.

Section VI demonstrates how graphical displays, such as stress maps and shortest-path "trees" (connectivity graphs), can be powerful tools that highlight the nature of the bicycling network and provide a strong basis for the selection of links to be added to the network.

In Section VIII we introduce a summary measure of connectivity for a city or a region: *the fraction of trips that could be made by bicycle without exceeding a given level of traffic stress and without an undue level of detour.* In the San José case study, where bike commute share is only 0.6 percent,¹ this measure is applied for work trips, using the regional work trip table. (It could just as well be applied for other trip purposes or for all trips; however, data on work trips is often more readily available.) If the current state of the bicycling network is such that only a small fraction of the work trips people make (by any mode) could be made by bicycle without using high-stress links, it should not be surprising that the bicycling share of trips is low.

In Section IX, a case study illustrates how the proposed measures of connectivity might be used in a planning context. It measures connectivity for San José's bicycling network in existing conditions and, for comparison, after a slate of improvements is made, yielding a quantifiable measure of how much this slate of improvements has increased the fraction of work trips that could be made by bike.

OTHER SECTIONS OF THE REPORT

Section VII describes the use of census blocks as the geographic unit of demand in network modeling and analysis. Section X discusses data and modeling issues. Section XI offers conclusions.

II. LEVELS OF TRAFFIC STRESS

CLASSIFYING POPULATIONS BY TOLERANCE FOR TRAFFIC STRESS

There are two popular schemes for classifying cyclists and potential cyclists according to their affinity for different kinds of bicycling facilities. One is the A, B, C scheme based on cyclist skill, first published by FHWA² and used implicitly in the *AASHTO Guide for the Development of Bicycling Facilities*:³

A = Advanced cyclists whose greater skill enables them to share roads with motor traffic. Moreover, they are unwilling to sacrifice speed for separation from traffic stress.

B = Basic adult cyclists, who lack the “skill” to confidently integrate with fast or heavy traffic.

C = Children cyclists, less capable than class B at negotiating with traffic and more prone to irrational and sudden movements.

Classes A and B are assumed to be very different, in that class B seeks separation from traffic, while class A welcomes integration with traffic, and often sees separation from traffic as a challenge to their right to ride in the road. The AASHTO Guide asserts a dichotomy between the needs of classes A and B, declaring that facilities serving one group will not serve the other because separation from traffic (in their view) almost always involves a compromise in speed, which class A cyclists hold paramount.

The AASHTO and FHWA publications that advance this scheme offer no estimates of the fraction of the population belonging to each class, though simple observation of the low bicycle ridership in America suggests that class A represents a very small fraction of the overall population. In keeping with the label “advanced” and a classification based on “skill,” the AASHTO Guide asserts that with education and experience riding a bike, people in class B will migrate to class A, suggesting that facilities developed for class B may be a poor investment.

Another classification scheme has been developed by Roger Geller, Portland’s bicycle coordinator.⁴ Based on a survey of residents’ attitudes both in general and toward bicycle facilities available in the Portland area, it divides the population into 4 classes, as illustrated in Figure 3.

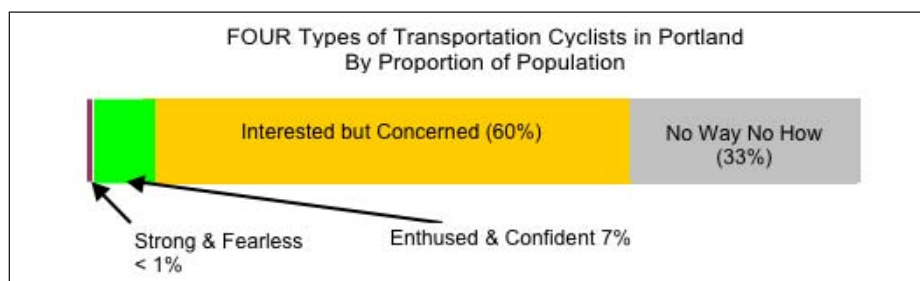


Figure 3. Portland’s Classification Scheme for the Population

Source: Geller, n.d.

Geller also estimates the fraction of the population belonging to each class, as shown in the figure. The “strong and fearless” respond well to riding in almost any traffic conditions and correspond to the class A riders of the FHWA scheme; they are said to represent less than one percent of the population. The “enthused and confident” don’t show that same tolerance for mixing with fast, turbulent traffic, but respond well to riding in bike lanes along arterial streets and to sharing smaller roads with traffic. The “interested but concerned” find situations in which they have to negotiate with traffic streams uncomfortable, but respond well to standalone paths and streets with little and slow traffic. The “No Way No How” group is not interested in riding a bicycle at all.

A classification based on tolerance for traffic stress (such as Geller’s) rather than skill seems more fruitful for bicycle network planning. Judging from the very small fraction of Americans who ride bikes (except in cities with low-stress bikeways), the skill-based classification scheme would leave all but one or two percent of adults in Class B, rendering such a classification almost useless. Classification by level of tolerance for traffic stress is consistent with studies that show people’s increasing affinity for lower-stress bicycling environments and indicate that traffic danger is the chief impediment to bicycling.⁵ The concept of intolerance for traffic stress also explains the enormous difference in bicycle use between the U.S. and European countries such as the Netherlands and Denmark,⁶ where separation from traffic is a fundamental principle of bicycle facility design. It also explains the rapid growth in bicycling seen in cities such as Portland that have invested heavily in low-stress bicycling facilities.⁷ A recent study of large American cities confirms that bicycling rates are higher in cities with more bike paths and bike lanes.⁸

This research adopts Geller’s classification scheme based on tolerance for traffic stress, but with the large “interested but concerned” class divided into two, one for children and one for adults. The more limited ability of children to make difficult crossings, their lower speed (which increases the speed differential to motor traffic), and their limited ability to interact with streams of traffic (as opposed to dealing with isolated motor vehicles) demands a greater degree of separation from traffic stress than that required by adults. Thus, ignoring the “No Way No How” segment of the population, our adopted scheme has four classes of bicycle users.

LEVELS OF TRAFFIC STRESS FOR FACILITIES

Related to research on classifying people by their tolerance for traffic stress has been research on classifying bicycling facilities – links and intersections – by the degree of traffic stress they impose on cyclists. Best known is the Bicycle Level of Service (BLOS) model for on-street facilities.⁹ It is based on level of comfort ratings given by subjects who rode a course that included a variety of bikeway and traffic situations. By relating those comfort ratings to the characteristics of the various sites, they developed a formula for predicting the comfort rating that a person would assign to a roadway link based on such characteristics as the traffic speed, traffic volume, presence of a bike lane, presence of a parking lane, whether the area is residential or not, and amount of operating space afforded to bikes (through a bike lane, shoulder, or an extra-wide outside travel lane). The predicted ratings are then indexed to six levels of service, from A (the best) to F (the worst). A similar effort to rate bicyclist comfort at intersections was not as successful.¹⁰ The BLOS

model for links has been adopted as a method for determining multimodal Level of Service in the Highway Capacity Manual¹¹ and is often used in bicycle network planning studies to identify streets with higher and lower levels of traffic stress.

A parallel research effort developed the Bicycle Compatibility Index or BCI.¹² Like the BLOS, it results in a formula for a comfort index based on bikeway, road, and traffic characteristics. While the BCI and BLOS formulas differ in form, their results are similar.

The BLOS and BCI classification schemes were deemed inadequate for this research for several reasons. First, they require data that is not readily available – particularly, traffic volumes and lane widths. Second, their complicated formulas are “black boxes” that conceal the relationship between level of service and attributes of a street such as traffic speed or volume. That is, not even a knowledgeable person could look at a street, or see all the data that applies to a street, and recognize or know what its BLOS or BCI score is without resorting to complex calculations. Third, the levels of service these models refer to have no meaning either to roadway managers or to the general public, other than “A is better than B, which is better than C,” and so forth.

We propose in this research a new classification scheme with four levels of traffic stress (LTS), corresponding directly to the four classes of the population described earlier. They are defined in general terms in Table 1. Specific criteria for these four levels of traffic stress are given in Sections III-V.

The proposed four-level classification scheme is anchored by LTS 2, whose criteria essentially mimic Dutch standards for bicycle traffic facilities.¹³ This is the level of tolerance that is mapped to the mainstream, traffic-intolerant adult population, those who are “interested but concerned.” Dutch standards have been proven on a population basis to be acceptable to the mainstream population, since bikeways built according to those standards attract essentially equal male/female shares and high levels of bicycle use for all age groups.¹⁴ (By contrast, cycling in the U.S. is about 70 percent male, with very low participation rates by older people). LTS 1, mapped to children cyclists, demands greater separation from traffic turbulence and easier crossings, while LTS 3, mapped to Geller’s “enthused and confident” group, allows increased traffic stress comparable to bike lanes on many American arterials. LTS 4, mapped to the “strong and fearless,” corresponds to riding in mixed traffic at 35 mph or more, or in bike lanes or shoulders next to traffic at highway speeds.

Table 1. Levels of Traffic Stress (LTS)

LTS 1	Presenting little traffic stress and demanding little attention from cyclists, and attractive enough for a relaxing bike ride. Suitable for almost all cyclists, including children trained to safely cross intersections. On links, cyclists are either physically separated from traffic, or are in an exclusive bicycling zone next to a slow traffic stream with no more than one lane per direction, or are on a shared road where they interact with only occasional motor vehicles (as opposed to a stream of traffic) with a low speed differential. Where cyclists ride alongside a parking lane, they have ample operating space outside the zone into which car doors are opened. Intersections are easy to approach and cross.
LTS 2	Presenting little traffic stress and therefore suitable to most adult cyclists but demanding more attention than might be expected from children. On links, cyclists are either physically separated from traffic, or are in an exclusive bicycling zone next to a well-confined traffic stream with adequate clearance from a parking lane, or are on a shared road where they interact with only occasional motor vehicles (as opposed to a stream of traffic) with a low speed differential. Where a bike lane lies between a through lane and a right-turn lane, it is configured to give cyclists unambiguous priority where cars cross the bike lane and to keep car speed in the right-turn lane comparable to bicycling speeds. Crossings are not difficult for most adults.
LTS 3	More traffic stress than LTS 2, yet markedly less than the stress of integrating with multilane traffic, and therefore welcome to many people currently riding bikes in American cities. Offering cyclists either an exclusive riding zone (lane) next to moderate-speed traffic or shared lanes on streets that are not multilane and have moderately low speed. Crossings may be longer or across higher-speed roads than allowed by LTS 2, but are still considered acceptably safe to most adult pedestrians.
LTS 4	A level of stress beyond LTS3.

ACCEPTABLE LEVEL OF DETOUR

Cyclists have a limited willingness to go out of their way to find a lower-stress bike route. If the shortest route that avoids high-stress links involves too much detour, many cyclists will not consider that route acceptable.

One study¹⁵ of nonrecreational cyclists in Vancouver, B.C., found that 75 percent of cyclist trips were within 10 percent of the shortest distance possible on the road network, and 90 percent were within 25 percent. (They found virtually identical results for automobile trips.) This small level of average detour is consistent with a 1997 study of bicycle commuters.¹⁶ However, they also found that people were more likely to go out of their way to take a route with more green cover and more bicycle-actuated signals. Broach, Glebe, and Dill¹⁷ found that commuting cyclists in Portland, Oregon were willing to add 16 percent on average to their trip length to use a bike path, and to add 11 percent to use a low-stress route using local streets (a “bike boulevard”). For non-commuting cyclists, those figures are 26 percent and 18 percent, respectively.

The detour criterion used in this study specifies that an acceptable lower-stress route should not be more than 25 percent longer than the shortest possible route using links of any level of stress. For short trips, the criterion was that a lower-stress route should be no more than 0.33 miles longer than the shortest route (0.33 miles require two minutes travel time at the relaxed pace of 10 mph). More formally, a route between two points limited to links with traffic stress level of k or less and having length L_k is acceptable with respect to detour if either of the follow conditions are true:

- $L_k / L_4 \leq 1.25$; OR
- $L_k - L_4 \leq 1760$ ft. (note: 1760 ft. = 1/3 of a mile, and takes about two minutes travel time)

where L_4 = length of the shortest path between the pair of points using links up to level of stress 4 (which include all links in the road and path network except highways on which bicycling is not permitted).

For future research, a more refined detour measure could consider travel time and effort as well as distance. Sometimes one route presents a speed advantage over another – e.g., the most direct route along a main street might require many stops, while a less direct route using a path along a river might require few stops. Cyclists' desire to minimize travel time can be expected to lead to a willingness to detour to the faster route. Routes with uphill require more effort (and usually involve lower speed). In this research, the effects of differential speed and effort were not accounted for in the detour criteria.

STRESSORS OTHER THAN TRAFFIC

Further research might consider factors besides traffic that impose stress on cyclists. They include steep hills, pavement quality, crime danger, noise, aesthetics of the surroundings, and absence of lighting or snow removal, which can affect seasonal or temporal availability. They have not been accounted for in this research because of the overwhelming effect of traffic stress in deterring cycling. However, they could conceivably be incorporated into the framework of this methodology. Factors that have a cumulative effect and that can be compensated could be accounted for using a generalized distance function within the framework of acceptable detour; they include, for example, steep grades (since riders will usually accept short segments of steep climb, but will try to avoid long uphill segments). Factors that, in themselves, can render a link unacceptable ("weakest link" factors), such as crime danger, could be incorporated into the stress criteria. Alternatively, the methodology could be generalized to model stress along several dimensions (e.g., stress from traffic, crime, pavement roughness), with the population similarly classified along multiple dimensions (e.g., a certain fraction of the population will accept safety stress up to level 2, crime stress up to level 3, and pavement stress up to level 2), with subnetworks defined and analyzed for each combination.

III. TRAFFIC STRESS CRITERIA FOR SEGMENTS

This section describes traffic stress criteria for segments between intersections. (Later sections give criteria for intersection approaches and crossings.) Criteria are given for three classes of bikeways: paths that are physically separated from traffic, bike lanes, and streets with mixed traffic.

The criteria chosen aim to account for the factors that determine the stress cyclists feel, while relying on variables that are commonly available or easily measured. Data sources used for the application in San José and adaptations required due to data unavailability are also discussed. The main data sources were:

- A regional street database which includes data on each street segment including its geographical coordinates, curb-to-curb width, number of lanes, width of median, speed limit, and functional class (residential, arterial, freeway).
- A regional traffic signal database indicating which intersections have traffic signals.
- A regional map of bike and pedestrian facilities that includes standalone trails and small links for non-motorized traffic – such as footbridges over freeways – and shows the location of bike lanes.
- Data on bike-lane width obtained from field measurements on streets with bike lanes.

PHYSICALLY SEPARATED BIKEWAYS

Bikeways that are physically separated from motor traffic have the lowest level of traffic stress between intersections, LTS 1. They include standalone paths as well as those that run alongside a road that may be called cycle tracks, sidepaths, or segregated lanes. Means of physical separation from motor traffic include, but are not limited to, curbs, raised medians, parking lanes, and flexible bollards.

This category includes shared-use paths as well as bicycling-only facilities. (While there can be some stress in sharing a path with pedestrians, it is not in the same class as traffic danger; it is more akin to congestion which can force a traveler to go slow, and, unlike traffic danger, is rarely a factor that keeps people from riding a bike.) It does not include sidewalks unless they have been designated for bicycling or as shared-use paths.

BIKE LANES

Bike lanes are space on the roadway designated by markings for exclusive use by bicycles, except for possible occasional encroachment by motor vehicle to access parking places or intersecting streets and driveways.

Bike lanes can exhibit the full range of traffic stress. Where they have ample width and are positioned on a road whose traffic is slow and simple (a single lane per direction), they can

offer cyclists a low-stress riding environment. However, bike lanes can also present a high-stress environment when positioned on roads with highway speeds or turbulent traffic, or next to high-turnover parking lanes without adequate clearance. The way bike lanes are treated on intersection approaches, often forcing cyclists to merge with motor traffic, can also add considerably to the stress they impose on riders; that effect is covered in Section IV.

Criteria for bike lanes alongside parking lanes are given in Table 2; those for bike lanes that are not alongside a parking lane are given in Table 3. There are criteria along four dimensions: street width (i.e., number of lanes), bicycle operating space, speed limit or prevailing speed, and bike lane blockage. For any given segment, these criteria aggregate following the weakest link principle: the dimension with the worst level of stress governs. For this reason, traffic stress levels in the tables that follow use notations such as “LTS \geq 2,” which means the factor puts a floor on traffic stress at level 2. For example, if a segment’s street width matches the criteria for LTS \geq 1, its prevailing speed matches LTS \geq 2, and its bike lane blockage matches LTS \geq 3, then the segment as a whole has LTS 3.

Table 2. Criteria for Bike Lanes Alongside a Parking Lane

	LTS \geq 1	LTS \geq 2	LTS \geq 3	LTS \geq 4
Street width (through lanes per direction)	1	(no effect)	2 or more	(no effect)
Sum of bike lane and parking lane width (includes marked buffer and paved gutter)	15 ft. or more	14 or 14.5 ft. ^a	13.5 ft. or less	(no effect)
Speed limit or prevailing speed	25 mph or less	30 mph	35 mph	40 mph or more
Bike lane blockage (typically applies in commercial areas)	rare	(no effect)	frequent	(no effect)

Note: (no effect) = factor does not trigger an increase to this level of traffic stress.

^a If speed limit < 25 mph or Class = residential, then any width is acceptable for LTS 2.

Table 3. Criteria for Bike Lanes Not Alongside a Parking Lane

	LTS \geq 1	LTS \geq 2	LTS \geq 3	LTS \geq 4
Street width (through lanes per direction)	1	2, if directions are separated by a raised median	more than 2, or 2 without a separating median	(no effect)
Bike lane width (includes marked buffer and paved gutter)	6 ft. or more	5.5 ft. or less	(no effect)	(no effect)
Speed limit or prevailing speed	30 mph or less	(no effect)	35 mph	40 mph or more
Bike lane blockage (may apply in commercial areas)	rare	(no effect)	frequent	(no effect)

Note: (no effect) = factor does not trigger an increase to this level of traffic stress.

CRITERIA RELATED TO STREET WIDTH

Street width is measured in number of through traffic lanes. The number of lanes directly affects the traffic environment. Multilane streets, in contrast to those with a single lane per direction, promote higher traffic speeds, and their traffic is more “turbulent” in the sense of being less confined and predictable. A multilane environment decreases a cyclist’s noticeability to left-turning and cross traffic at driveways and intersections. Apart from the direct effect of multiple lanes, “number of lanes” also serves as a surrogate for traffic volume, a parameter that is not generally available in street databases.

In Dutch bikeway design criteria, number of lanes is a more critical variable than traffic volume. Dutch criteria, our model for LTS 2, specify that bike lanes should not be applied to streets with more than one through lane per direction. However, in practice, many older Dutch streets with two lanes per direction, no parking, and a dividing median also have bike lanes and are well used. Having a median and no parking lane makes traffic less turbulent than it would be otherwise. Therefore, LTS 2 criteria given in Tables 2 and 3 reflect that practice. Turn lanes are accounted for in criteria presented in Section IV related to intersection approaches.

The San José streets database includes number of lanes but counts turn lanes as well as through lanes, which can distort figures on approaches to signalized intersections. However, its streets almost always have the same number of through lanes in each direction, and rarely have more than one turn lane, so that, for example, the condition “Number of Lanes = 2 or 3” will identify segments with one through lane per direction in most cases.

CRITERIA RELATED TO OPERATING SPACE

For bike lanes not alongside a parking lane, operating space is the bike lane width. Width should be measured from the curb (or street edge) to the outside travel lane, including gutter and any marked buffer as well as the bike lane itself. A study of Dutch bicycling cities emphasizes how the wide bike lanes in cities like Zwolle offer a low-stress environment.¹⁸ In the U.S., Davis, California uses wide bike lanes (typically, 6 or 7 ft. wide) which have been successful at attracting the mainstream population to bike riding, thus demonstrating that they impose little stress on cyclists.

Next to a parking lane, cyclists must contend with a “dooring” hazard on the right (“dooring” means colliding with the suddenly opened door of a parked car) and the hazard of passing traffic on the left. The critical dimension is not the bike lane width *per se*, but rather its reach from the curb, which is the combined width of the parking and cycling lanes, plus any marked buffer. With a reach of 15 ft., cyclists can ride with ample clearance from hazards on both sides. With 14 ft., cyclists can usually avoid both hazards, but have to maintain a carefully chosen, narrow track that keeps risk low on both sides; this need to keep to a narrow track increases stress. With 13 ft. or less, cyclists are forced to accept either some dooring risk on the right, or ride such that they encroach into the adjacent travel lane, a tradeoff that involves considerable stress except on low-speed, residential streets. Still, as Van Houten and Seiderman’s study¹⁹ demonstrates, the stress of a narrow bike lane next

to parking is still less than the stress of riding in mixed traffic, which is why a bike lane's operating space, even if tight, does not trigger a LTS 4.

Data on bike lane width and bike lane reach were obtained manually from measurements made in the field or using satellite photos supplied by private entities such as Google Maps. Because there is a limited set of streets with bike lanes, this task, while labor-intensive, was manageable in scope.

CRITERIA RELATED TO SPEED

Traffic speed clearly affects cyclists' comfort. Measures of observed speed are generally not available on a widespread basis. Speed limit can be an adequate surrogate if a city systematically adjusts the speed limit to the prevailing speed or uses systematic means such as speed cameras or traffic calming to make actual speeds comply with the speed limit. The former is the case in San José, where one can see a wide variety of speed limits; they are typically 25 mph on residential streets with no centerline and 25, 30, 35, 40, or 45 mph on higher-order streets. These speed limits generally correspond with actual traffic speeds; therefore, speed limit was used as the prevailing speed measure in the San José application.

In other cities, speed limit may not be a good indicator of operating speed. In Boston, for example, the statutory speed limit of 30 mph applies equally to local streets, where traffic often runs at speeds of 25 mph, and to arterials where prevailing speeds can exceed 35 mph. In such a case, it might be possible to develop a function that predicts prevailing speed from available data such as number of lanes, functional class, intersection spacing, and possibly other factors in addition to speed limit.

CRITERIA RELATED TO BIKE LANE BLOCKAGE

On some street segments—particularly those in commercial areas—bike lanes are frequently blocked by double-parked cars, cars maneuvering into parking places, people getting out of their parked cars, and similar factors, forcing cyclists to merge into the adjacent travel lane. Dutch criteria for many years have recognized this effect and specified that in areas with high parking turnover and occupancy (where double parking is likely), the bikeway should be a cycle track rather than a bike lane.²⁰ Our criteria specify that bike lanes that are frequently blocked increase the stress to level 3.

A reasonable way of assigning values is to assume “frequent” for bike lanes in commercial areas, and “rare” elsewhere. For the San José application, because the street database did not identify which blocks are commercial and because local riders indicated that bike lanes being blocked is not a common problem in the city, bike lane blockage was always assumed to be rare.

MIXED TRAFFIC

Where cyclists share space on the road with motor traffic, level of traffic stress is assumed to be unaffected by signage (e.g., “Bike Route” or “Share the Road” signs), shared-lane

markings, or having a wide outside lane. Studies of shared-lane markings have shown that they have a small beneficial effect but nothing comparable to the benefit of designating an exclusive bicycling zone by marking a bike lane. Likewise, studies of wide-lane conversions (when a wide lane is divided into a travel lane and bike lane) have consistently shown that bicyclists feel less stress when a bike lane line formally demarks the bicycling zone, evidenced by the shift in cyclist position away from right side hazards.²¹ With both the BLOS and BCI models cited earlier,²² bike lane stripes improve the level of service by almost one full letter grade (e.g., C to B, or B to A), beyond the effect of the operating space afforded by the bike lane.

We propose that level of stress when riding in mixed traffic depends on the prevailing traffic speed and street width (number of lanes); criteria are shown in Table 4. In multilane traffic with speeds of 30 mph or greater, level of traffic stress is 4. LTS 2 can be achieved with mixed traffic only on streets with one lane per direction, consistent with Dutch criteria that do not allow mixed traffic as an acceptable bicycle accommodation for roads with multilane traffic.

Table 4. Criteria for Level of Traffic Stress in Mixed Traffic

Speed Limit	Street Width		
	2-3 lanes	4-5 lanes	6+ lanes
Up to 25 mph	LTS 1 ^a or 2 ^a	LTS 3	LTS 4
30 mph	LTS 2 ^a or 3 ^a	LTS 4	LTS 4
35+ mph	LTS 4	LTS 4	LTS 4

Note: ^a Use lower value for streets without marked centerlines or classified as residential and with fewer than 3 lanes; use higher value otherwise.

In Dutch practice, mixed traffic is only allowed on streets without marked centerlines. Where a centerline is marked, it gives each directional stream of motor traffic a designated lane, and by guiding motorists to stay on their half of the road, creates a conflict with bicycles who generally keep to the right. By contrast, the absence of a centerline directs road users to share space, and therefore allows cyclists to claim their space on the right side of the road without appearing to be invading the cars' designated space. On streets without centerlines and with low traffic (the Dutch manual sets a threshold of 2,000 vehicle/day), motorists tend to ride in the middle of the road, leaving the edges as uncontested space for cycling, and when forced to merge to the right by an oncoming car, they usually do so in a way that respects the priority of any cyclist that may be present. In contrast, above 4,000 vehicles/day, traffic tends to divide into two lanes even if a centerline isn't marked. Therefore, for streets with one lane per direction, it would be ideal to account both for whether a centerline is marked and whether the daily traffic volume is in the range 0-2,000, 2,000-4,000, or greater than 4,000 vehicles per day.

Because neither volume data nor the presence of a centerline were available in the San José database, we used the residential classification as a surrogate, since that classification is mainly applied to streets with no centerline and low traffic volumes. On multilane roads, traffic volume does not enter into the traffic stress criteria at all.

IV. TRAFFIC STRESS CRITERIA FOR INTERSECTION APPROACHES

Where streets approach signalized intersections, auxiliary turn lanes are often added. The effect on cyclists of added left-turn lanes can be ignored because cyclists generally stay to the right; however, added right-turn lanes challenge a cyclist's normal position and create a weaving conflict. This section is concerned with the traffic stress caused by conflicts with right-turning traffic.

The stress level associated with an intersection approach should be aggregated with the stress level already assigned to a segment following "weakest link" logic. That way, the characteristics of an intersection approach can make a segment's LTS worse, but not better. For example, if segment-based criteria result in a segment being assigned LTS 3 while an intersection approach on either end of the segment has $LTS \geq 2$, the combined stress level remains LTS 3; but if the approach has LTS 4, the combined stress level for the segment will be LTS 4.

CRITERIA FOR POCKET BIKE LANES

A "pocket bike lane" is a bike lane positioned between a right-turn lane and a through lane. Criteria are given in Table 5. Dutch guidelines for pocket lanes,²³ which are the basis for the proposed LTS 2 criteria, are twofold:

- The right-turn lane must begin abruptly to the right of the bike lane with the bike lane continuing straight, so that priority is unambiguously with the cyclists where cars cross the bike lane to enter the right-turn lane.
- The geometry should be such that traffic speed in the right lane does not exceed 20 km/h (13 mph), so that cyclists in a pocket lane do not have to deal with cars passing on both sides. Such a low traffic speed is achieved by keeping the right-turn lane short, making the turning angle no greater than 90 degrees, and giving corner curb returns a small radius.

Where pocket lane entries are configured in a way that forces cyclists to merge across traffic entering the right-turn lane, this is highly stressful to cyclists since priority is ambiguous and cyclists have to look over their shoulder to negotiate with arriving traffic that could potentially be moving fast. This situation occurs whenever the introduction of a right-turn lane forces the bike lane position to shift to the left, such as when the right travel lane becomes a right-turn lane. In these situations, the bike lane either veers to the left, or disappears for 100 ft. or so and then reappears in its new, leftward position. These stressful configurations are part of standard road design practice in many parts of the U.S. (e.g., California MUTCD 2012, p. 1,379, paragraph 19).

In our application to San José, information about the configuration of pocket bike lanes was not readily available, and, due to problems with field data collection, was not properly coded. Because San José streets with bike lanes rarely have the low-stress pocket bike lane configuration described above, all segments with pocket bike lanes were given an

LTS floor of 3, except in places known to have dual right-turn lanes (which usually occur only at junctions with freeway ramps), where LTS is 4. San José's streets have some situations in which a pocket bike lane would merit LTS 4 according to the proposed criteria; however, in those situations, the base level of traffic stress for the segment is usually 4 already, and so using a floor of LTS 3 for the pocket bike lane has little distorting effect.

Table 5. Level of Traffic Stress Criteria for Pocket Bike Lanes

Configuration	Level of Traffic Stress
Single right-turn lane up to 150 ft. long, starting abruptly while the bike lane continues straight, and having an intersection angle and curb radius such that turning speed is ≤ 15 mph.	LTS ≥ 2
Single right-turn lane longer than 150 ft. starting abruptly while the bike lane continues straight, and having an intersection angle and curb radius such that turning speed is ≤ 20 mph.	LTS ≥ 3
Single right-turn lane in which the bike lane shifts to the left but the intersection angle and curb radius are such that turning speed is ≤ 15 mph.	LTS ≥ 3
Single right-turn lane with any other configuration; dual right-turn lanes; or right-turn lane along with an option (through-right) lane.	LTS = 4

CRITERIA FOR MIXED TRAFFIC IN THE PRESENCE OF RIGHT-TURN LANES

Where there is an auxiliary right lane and no bike lane, either because the street has no bike lanes or where the bike lane is dropped in order to devote space to an auxiliary lane, bicyclists will be in a high-stress situation unless the right-turn lane is so little used and has such low traffic speeds that cyclists can share it with right-turn cars as a *de facto* bike lane. Low right-turning volumes are often indicated by a very short turning lane. Markings that guide through cyclists to use the right-turn lane as a through bike lane are used in some states and are described in the NACTO Guide.²⁴ Criteria are found in Table 6.

If a street has a bike lane for part of the block, but the bike lane is dropped on an intersection approach, that block was coded as having no bike lane. Therefore, the need to ride in mixed traffic will be accounted for in the base segment's level of traffic stress.

Table 6. Level of Traffic Stress Criteria for Mixed Traffic in the Presence of a Right-turn Lane

Configuration	Level of Traffic Stress
Single right-turn lane with length ≤ 75 ft. and intersection angle and curb radius limit turning speed to 15 mph.	(no effect on LTS)
Single right-turn lane with length between 75 and 150 ft., and intersection angle and curb radius limit turning speed to 15 mph.	LTS ≥ 3
Otherwise.	LTS = 4

For the San José application, the data needed to apply this criterion were not systematically available and therefore were used in only a few cases. Most of the streets that have right-turn lanes are multilane arterials whose base segment level of stress was already 3 or 4, so it is likely that there are only a few cases in which omission of this factor distorted the calculated level of traffic stress.

V. TRAFFIC STRESS CRITERIA FOR CROSSINGS

Unsignalized crossings can be a barrier, especially to children but also to adults if the street being crossed has multiple lanes or fast traffic. Criteria for unsignalized crossings are presented in Tables 7 and 8. Dutch criteria for unsignalized crossings (which apply equally to pedestrians and cyclists) do not allow any crossing of more than two lanes. In this respect the LTS 2 criteria depart from Dutch practice by allowing crossings of streets with up to five lanes, where the speed limit is 30 mph or less. Such a crossing may be unpleasant and unsafe (statistically speaking), but it will not be a barrier to most American adults. An exception is when traffic volume is so high that gaps are rare, but data to support that kind of classification is not widely available.

In the proposed criteria, crossings are considered a barrier to traffic-intolerant adults when crossing a street with six lanes and any speed limit, or four lanes and a speed limit of 35 mph or greater. The presence of median refuge lowers the level of stress.

Table 7. Level of Traffic Stress Criteria for Unsignalized Crossings Without a Median Refuge

Speed Limit of Street Being Crossed	Width of Street Being Crossed		
	Up to 3 lanes	4 - 5 lanes	6+ lanes
Up to 25 mph	LTS 1	LTS 2	LTS 4
30 mph	LTS 1	LTS 2	LTS 4
35 mph	LTS 2	LTS 3	LTS 4
40+	LTS 3	LTS 4	LTS 4

Table 8. Level of Traffic Stress Criteria for Unsignalized Crossings With a Median Refuge at Least Six Feet Wide

Speed Limit of Street Being Crossed	Width of Street Being Crossed		
	Up to 3 lanes	4 - 5 lanes	6+ lanes
Up to 25 mph	LTS 1	LTS 1	LTS 2
30 mph	LTS 1	LTS 2	LTS 3
35 mph	LTS 2	LTS 3	LTS 4
40+	LTS 3	LTS 4	LTS 4

Signalized crossings do not usually present a barrier to cycling and were therefore not part of the criteria applied in this study. An exception that could be included is long crossings on streets where the signal phase serving the cyclist is too short for a slow cyclist to cross before conflicting traffic is released. However, because such situations are unusual and because data on signal timings correlated with crossing length is not generally available, this factor was not addressed in the San José application.

APPLYING CROSSING EFFECT TO APPROACH LINKS

In standard network topology, crossings are not part of a link. For them to have an effect, either crossings have to be modeled as explicit multilink structures with a link for every possible path through the intersection – a technique used in transportation network modeling to account for turning delays, but at the cost of increasing the network size – or the effect can be placed on the link(s) approaching the crossing. We used the latter approach. That is, where a minor street meets a major street at an unsignalized intersection, the stress level for crossing the major street was applied to the minor street link(s) incident to the crossing. Stress levels due to a crossing are combined with stress levels from other factors in the usual, “weakest link” logic, meaning they govern the level of stress only if they are worse than the link’s stress is without the crossing effect.

For San José, the street database was updated with median width (zero if there is none), number of lanes, and presence of a traffic signal, from which the crossing stress could be determined. The challenge was in applying this stress to the appropriate links (i.e., the minor street, not the major street). A program was written to scan over all vertices to see which lacked a traffic signal; identify all of the legs (links) incident to the vertex; determine which legs belonged to the street with priority (based on which pair of legs have the most lanes, and allowing the legs of the priority street to differ in orientation by no more than 30 degrees); and finally to calculate and apply the crossing stress to the minor legs incident to that vertex.

Modeling the effect of stressful crossings on path choice is important, because if paths are chosen based only on the stress associated with links, shortest-path logic will try to link low-stress segments that meet on opposite sides of a wide street without accounting for the stress involved in the crossing. An example in San José is where Rosemary Lane, a low-stress local street, crosses Winchester Blvd. (speed limit = 35 mph). Winchester has seven lanes on the south side of that intersection and is six lanes wide on the north side, with no median or crosswalk and with an often-empty parking lane that makes the road seem even wider. The crossing is clearly dangerous and one that most people would avoid. Figures 4 and 5 show stress maps (links colored according to level of traffic stress) in the area before and after the crossing effect is applied. Before it is applied, there appears to be a continuous low-stress (green) path across Winchester using Rosemary. After the intersection effect is applied, the blocks of Rosemary touching Winchester have been assigned LTS 4. As a result, one can see that there is no longer a low-stress route in the area crossing Winchester Blvd, a finding that reflects reality and makes a significant difference to network connectivity. The figures show a similar effect where Latimer Street crosses Winchester. Because this section of Winchester has five lanes and a speed limit of 35 mph, the blocks of Latimer incident to Winchester have their level of traffic stress increased to LTS 3.

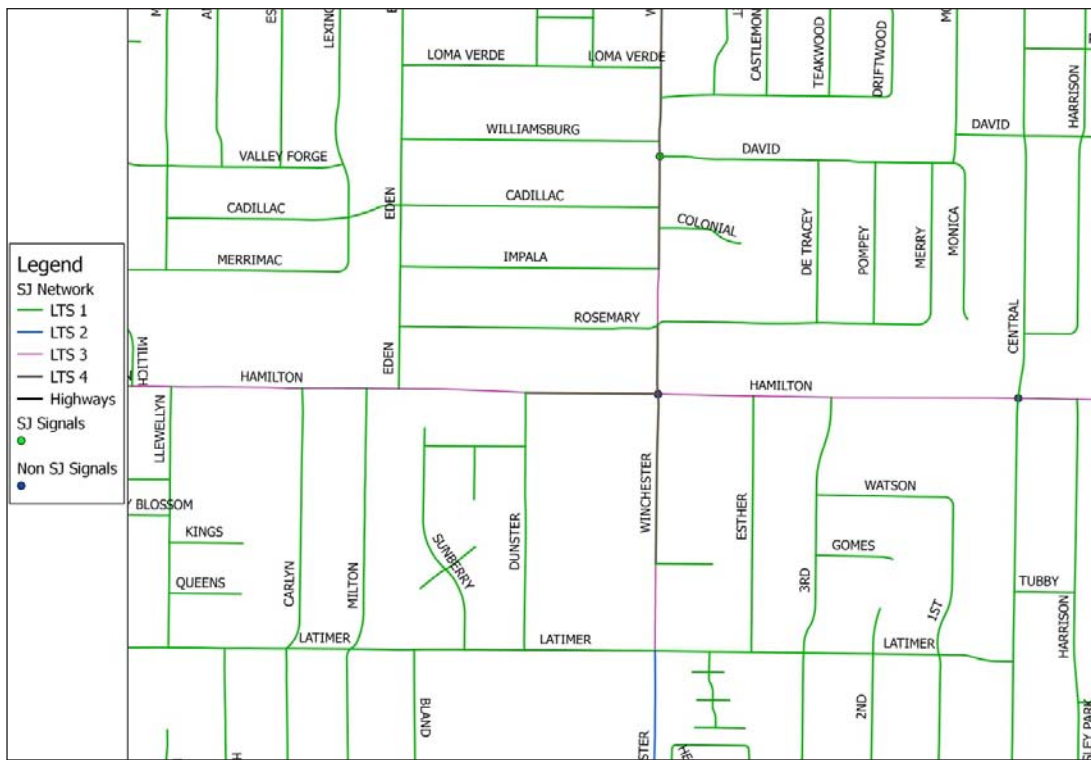


Figure 4. Stress Map Without Intersection Effect, Implying Low-Stress Routes Across Winchester Blvd. Using Rosemary Lane or Latimer St.

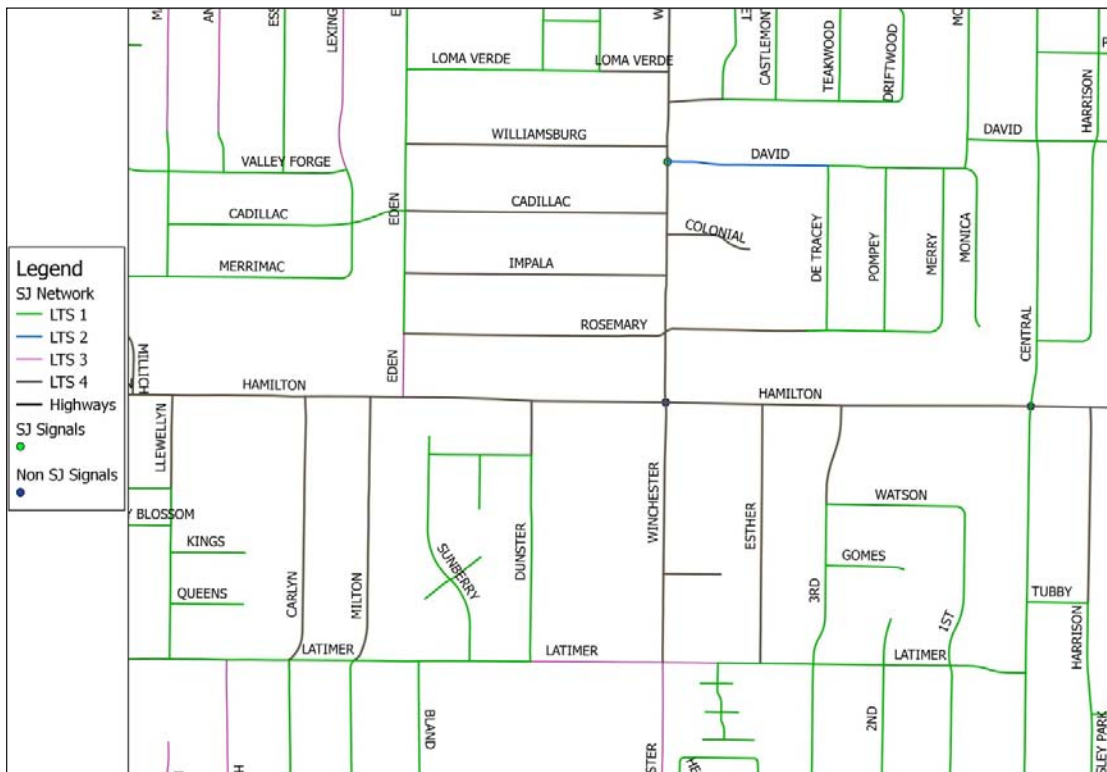


Figure 5. Stress Map With Intersection Effect Applied, Showing Absence of a Low-Stress Route Across Winchester Blvd.

VI. STRESS MAPPING

Using the criteria given in the previous sections, a software routine (written in C++, and running within the GIS environment) assigned a level of stress to every section of road and path in the city. An on-line map allows readers to scan and zoom over the entire city of San José; interested readers can see it at <http://www.axumcorp.com/bikenetwork.htm> and selecting the Metro San José Bike Network link.

It is worth noting the size of the street network used in this network analysis. It had over 36,900 edges and 29,200 vertices. The street network includes parts of some municipalities bordering San José since the shortest path between parts of San José can involve travel outside the city boundary.

DISTRIBUTION OF TRAFFIC STRESS LEVELS

A large-scale stress map of part of the city can be seen in Figure 6. San José State University (SJSU) and San José City College (SJCC) are labeled to help orient readers unfamiliar with the area. Stress level is coded by color: green = LTS 1, blue = LTS 2, violet = LTS 3, and brown = LTS 4. Thick black lines indicate freeways. When viewing the map, one is first struck by the prevalence of green, that is, LTS 1 routes. This stems from the fact that the majority of the city's road-miles are residential streets. Table 9 shows the distribution of segment miles by level of traffic stress. It is strongly bifurcated, with 64 percent at LTS 1 (mostly residential streets) and 20 percent at LTS 4 (wide, higher speed arterials), with relatively few road-miles at intermediate levels of stress.

Table 9. Distribution of Centerline Miles by Level of Traffic Stress

Stress	Level	Miles	Miles (percent)
Lowest	1	2,131	64 percent
Low	2	115	3 percent
Medium	3	276	8 percent
High	4	678	20 percent
Prohibited	5	134	4 percent
Total		3,334	100 percent

The city's arterial network can be seen as a grid of streets mostly in brown (LTS 4). Some arterials appear in violet (LTS 3) because they have bike lanes and/or lower speed limits. The stress of unprotected crossings can also be seen, as on many residential streets, blocks incident to an arterial are either brown (LTS 4) or violet (LTS 3).

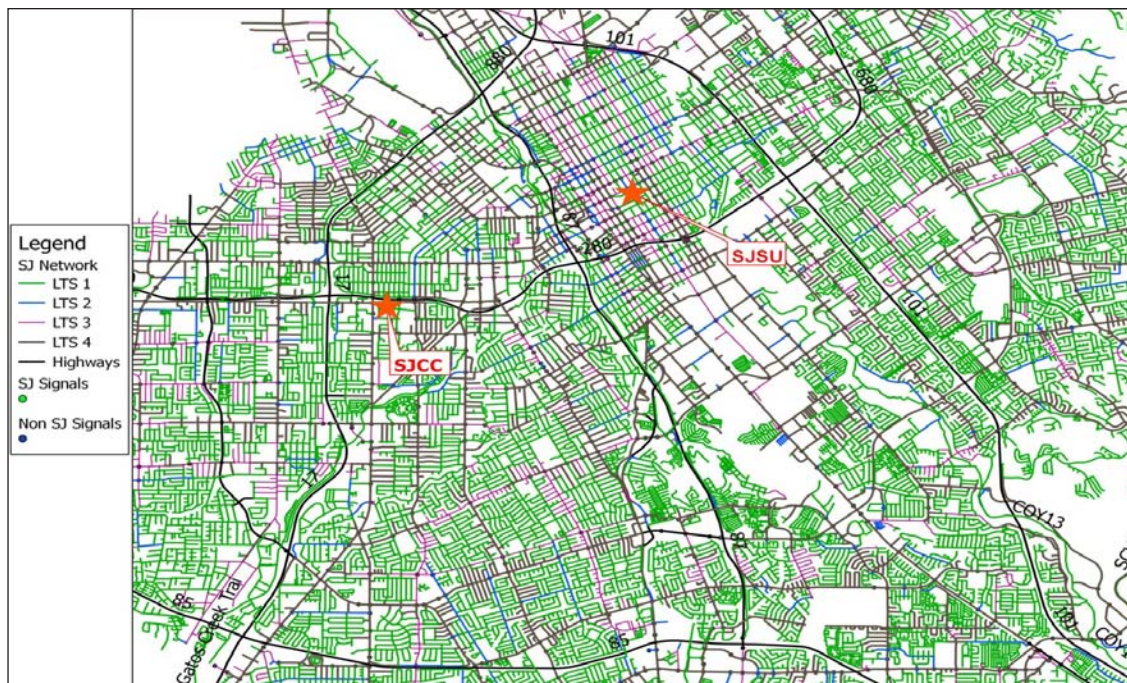


Figure 6. Stress Map With Downtown San José to the North

A map displaying only links at LTS 1 and 2 is displayed in Figure 7 for a subset of the area shown in Figure 6. (For orientation, the Los Gatos Trail emerges from the map's southwest corner, and Willow Ave. is the broken blue line across the top middle.) This is the bicycling network for the mainstream, traffic-intolerant population, and it has very poor connectivity. Much of this subnetwork consists of unconnected clusters, illustrating the typical situation in which a person cannot ride beyond the immediate neighborhood without using high-stress links.

There are some notable exceptions to this pattern of discontinuity. One is the regional trails (Guadalupe, Los Gatos, and Coyote Creek) that follow the creeks; however, because those trails are typically situated in ravines or on levees, they tend to be poorly connected to nearby residential streets. The trail connections occur primarily at high-stress roadways, thereby reducing their accessibility. Another exception is minor arterials with one lane per direction and bike lanes, appearing on the map as long sections of blue (speed limit = 30 mph) and violet (speed limit = 35 mph) and providing vital connections across the city. However, those facilities also have gaps, leaving the network quite unconnected except at stress level 4.

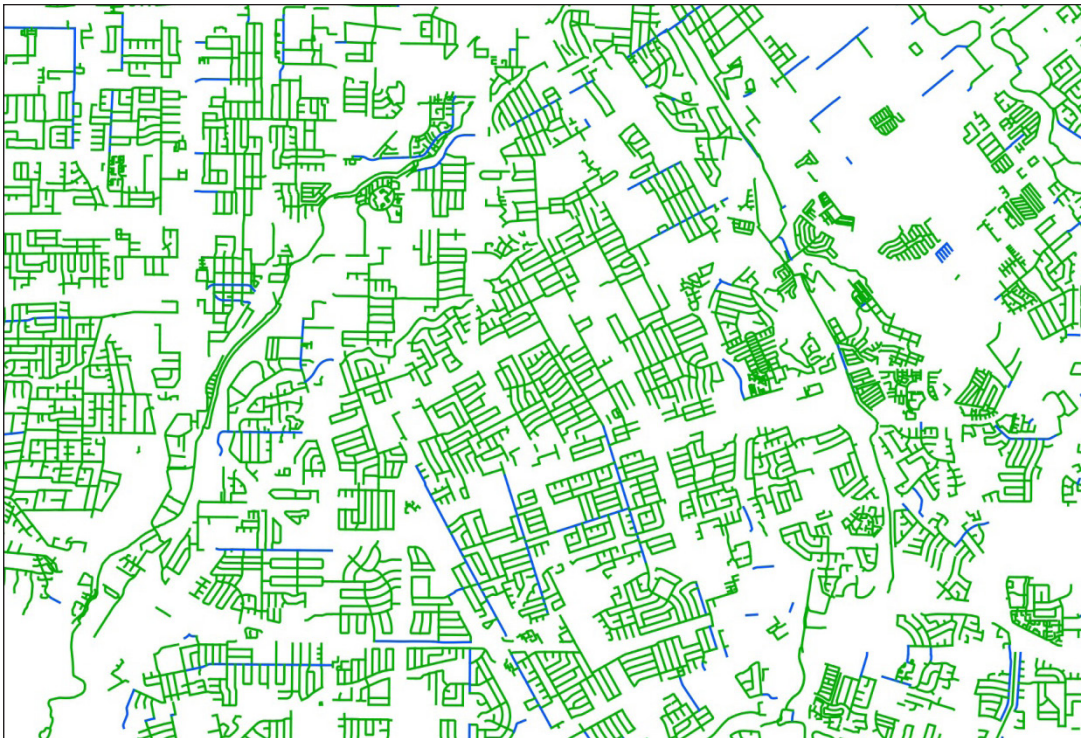


Figure 7. Stress Map Showing Only LTS 1 (Green) and LTS 2 (Blue) Links

ISLANDS AND BARRIERS

A network analysis tool was developed to find the shortest-path tree from any root vertex on a stress-limited subnetwork to every other node (vertex) in the network. Such a tool reveals “islands of connectivity,” that is, sets of links that are connected to one another but are not connected to the rest of the network. Figure 8 shows several such islands of connectivity for LTS 1. The only sizable islands are in the older parts of the city in which the local street network is dense and has few gaps. The very long, thin islands have off-road trails (Los Gatos in blue, Guadalupe in lime, and Coyote Creek in brown) as spines, together with the few low-stress streets that connect to them. Figure 9 shows connectivity islands at LTS 2. As expected, the islands are larger. Between them, but not highlighted, are barriers that can be crossed only at LTS 3 or greater. These maps illustrate that even though large masses of low-stress links, or “connectivity clusters,” exist throughout the city, they are of limited use for bicycle transportation if they lack low-stress interconnecting links. Like the islands of an archipelago, these link-rich “islands” seem enticingly close, yet they are inaccessible to most of the population.

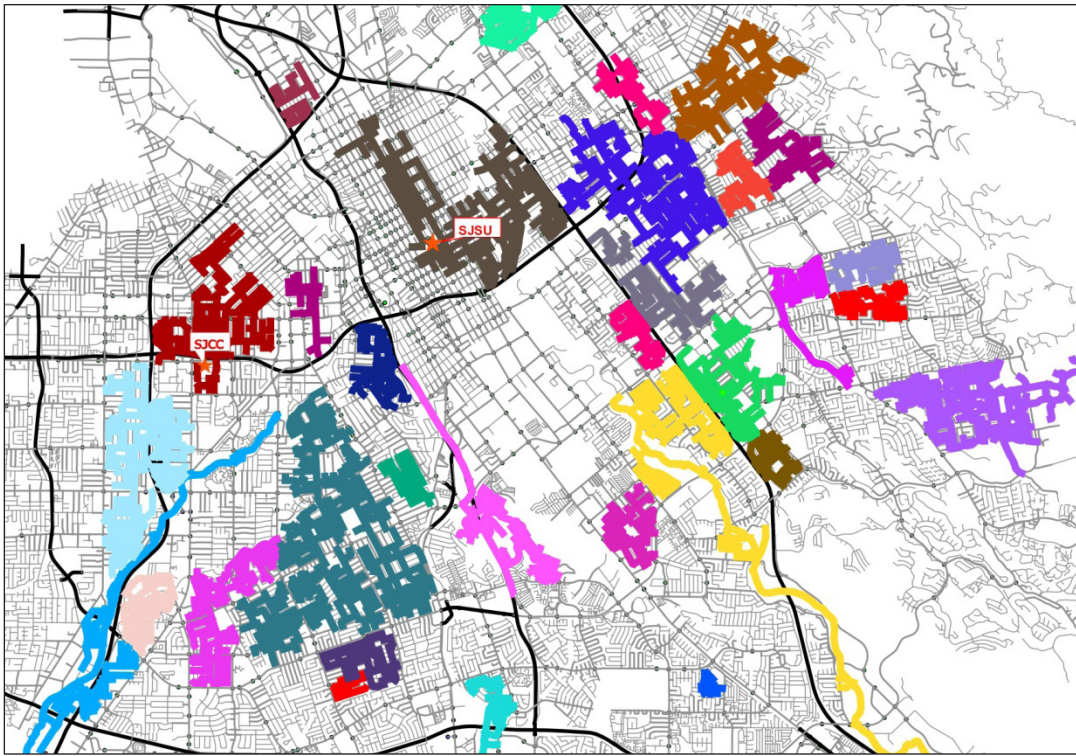


Figure 8. Some Connectivity Clusters at LTS 1

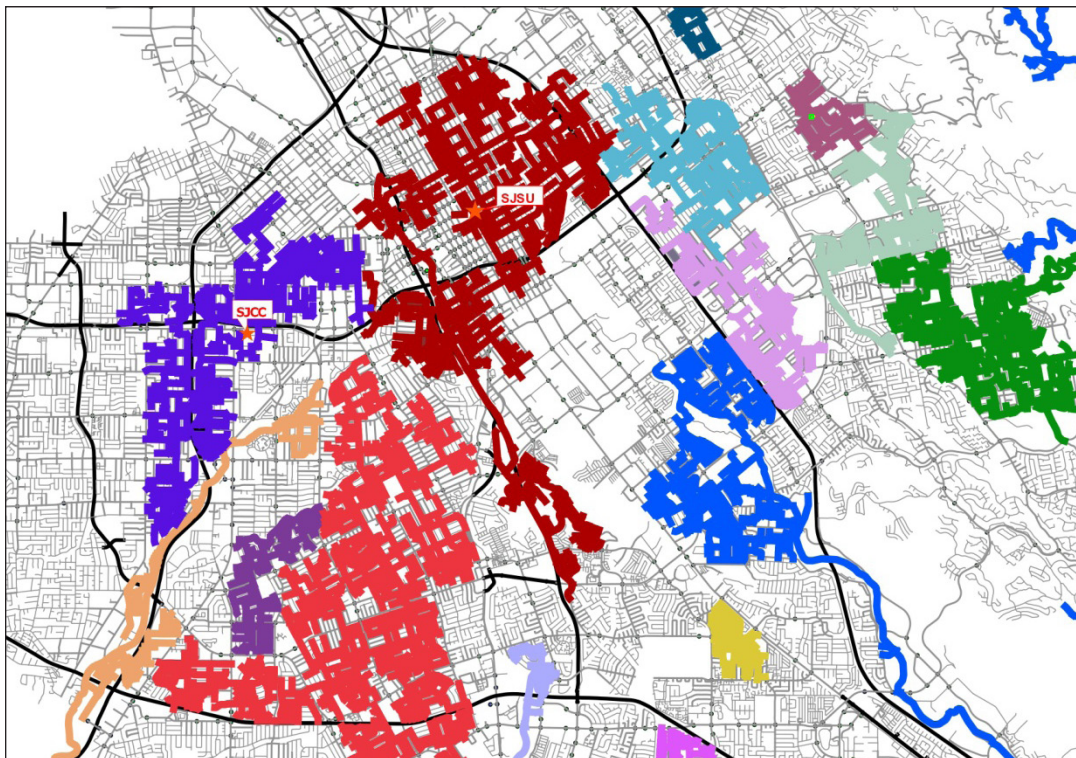


Figure 9. Some Connectivity Clusters at LTS 2

The looping shape of some of the clusters in Figure 9 illustrates the necessity of a criterion for limiting detour when assessing point-to-point connectivity. Connectivity clusters, though useful, cannot directly show which point-to-point pairs exceed the detour criterion.

Analysis of connectivity cluster maps reveals that there are three kinds of barriers that separate low-stress clusters from one another. In the discussion that follows several illustrative examples are given; readers are encouraged to explore others using online maps.

One common barrier is the natural and manmade type created by freeways, railroads, and creeks that require grade-separated crossings. Due to cost of grade-separated crossings, they tend to be widely spaced. In some cases, there are no crossings for a long distance. Where crossings do exist, the wide spacing concentrates traffic demand, and crossing points are often given multiple lanes to accommodate this demand, which makes them high-stress links. Crossings over these barriers often involve long approaches without intersections, allowing high traffic speeds. Freeway onramps and offramps are particularly stressful for bicyclists to cross. In the older parts of the city, freeway crossings with no on- or off-ramps are common, improving low-stress connectivity; however, in other parts of the city they are rare. For example, along Highway 101 in San José, between San Antonio Street (near downtown) and the city's southern boundary at Metcalf Street, a distance of 10 miles, the only crossings with LTS 2 or lower are the two crossings made by the Coyote Creek Trail. (Hellyer Avenue doesn't attain LTS 2 because of a freeway onramp; nor does Coyote Rd., with a speed limit of 35 mph and no bike lane on one side of the street.)

Low-stress, grade-separated crossings of such barriers have an enormous impact on connectivity. San José has 11 footbridges over some of its older freeways that link local streets severed by freeway construction (e.g., across I-280 at Monroe St. and across Highway 17 at Downing/Westfield). Low-traffic streets that cross freeways (without an interchange) or other barriers are also important connectors. One example is W. St. John St., which passes over Guadalupe Creek and under Highway 87 (however, it does not cross the railroad tracks just west of the creek, forcing cyclists to use a higher-stress crossing using Julian St. or Santa Clara St.). Another example is E. William St., which crosses Coyote Creek; however, it does not cross Highway 101. A counterexample is Dana Ave. in the northwest part of the city, a low-stress street on either side of Highway 880 that was unfortunately severed by freeway construction.

Arterial streets represent a second common barrier type. In San José, it is typical for local streets to meet arterial streets at 3-leg ("T") intersections. If the arterial has a high-stress environment, it effectively severs the local streets on either side from one another. Even if the local streets meet an arterial at an unsignalized 4-way crossing, the stress due to the lack of a safe crossing can keep them unconnected. Where an arterial's intersection with minor streets is signalized, the minor streets are often widened on the block approaching the arterial to accommodate the demand that concentrates at signalized crossings, with bike lanes sometimes eliminated or displaced in a way that creates a high-stress merge for bicyclists.

Figure 10 shows two examples of streets that would otherwise be excellent low-stress routes, but whose stress level rises where they are widened on intersection approaches: Monroe St. approaching Stevens Creek Blvd. near the Valley Fair Mall and Stokes St. approaching Bascom Ave. When those widenings (“improvements”) were constructed, there was no intention to negatively impact bicycling; however, adapting roads to increased motor traffic often leads to degrading the bicycling environment unless the needs of cyclists are explicitly accounted for.

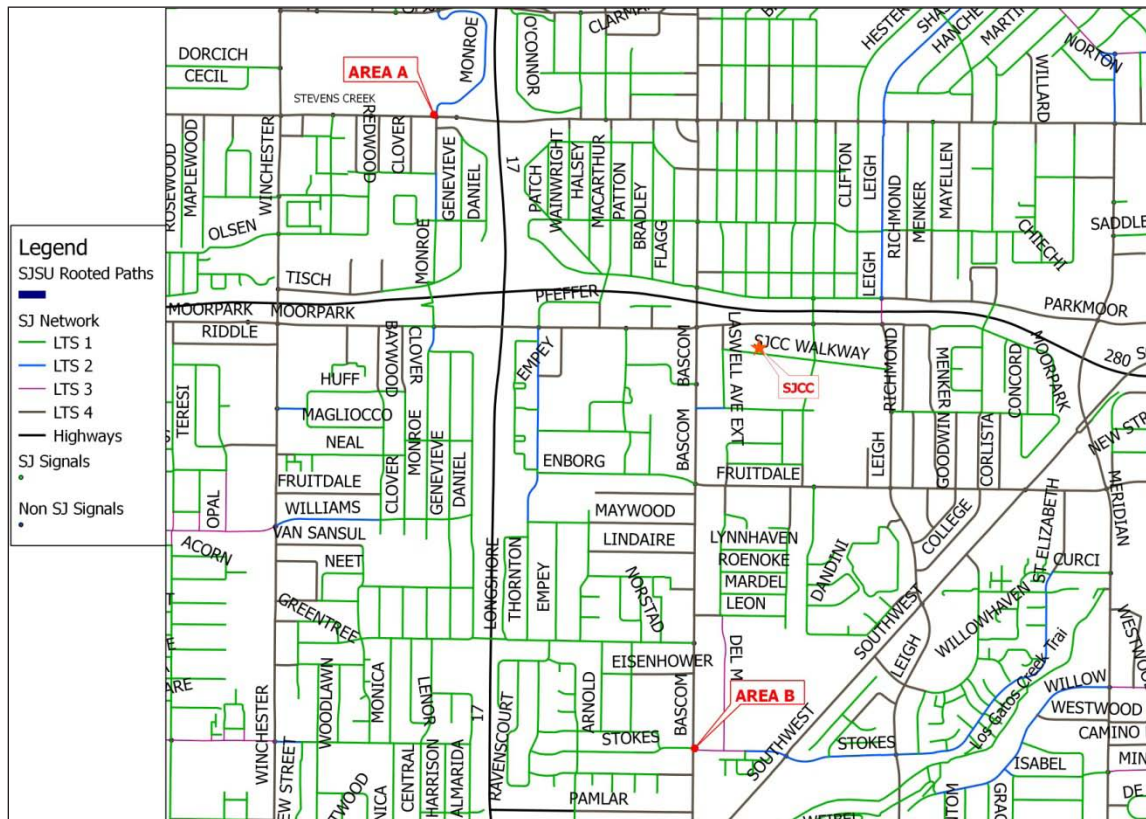


Figure 10. Widened Approaches to Arterials that Increase Stress Levels in Otherwise Low-Stress Routes

Note: Area A = Monroe St. at Stevens Creek Blvd.; Area B = Stokes St. at Bascom Ave.

A third type of barrier is created by breaks in the residential street grid. In the older sections of the city, the street grid is dense and has few breaks, while in more recently developed areas, grids are often deliberately incomplete in order to prevent cut-through motor traffic; an unfortunate side effect is that they also prevent low-stress through bicycle traffic, forcing bikes onto the arterials.

Where the discontinuity in the local street grid is due to a park or campus, providing public access paths through them can make a big difference in connectivity. Examples are the city’s Fair Swim Center (disconnecting Kilchoan Way from Crucero Drive) and the closed section of Sherman Street (a low-stress alternative to S. First St. in the East Virginia Neighborhood) at Oak, which is open to pedestrians but lacks the ramps needed to make it a bicycling connection. The city also has several examples of barricaded connections that prevent through traffic not only by cars but by bikes and pedestrians as well. A

positive example is the permeable barrier used to close Dry Creek Rd. near Cherry Ave.; it keeps through motor traffic off of Dry Creek Rd. while still providing a vital cut-through for bicycles and pedestrians. In contrast, the adjacent closure of Cherry Ave. is impermeable to pedestrians and bikes.

Whether the city's college campuses are a barrier or haven for bicycling depends on whether the wide footpaths and access drives through them are considered open to the public. Our maps and analysis treat those paths as available. Some of them play an important role in regional connectivity.

VISUALLY IDENTIFYING ROUTES AND CRITICALLY NEEDED IMPROVEMENTS

For network design, creating shortest-path trees rooted at various points, as illustrated earlier, helps an analyst to identify barriers. For a bicycling network to provide reasonably direct routes in all directions, it should provide closely spaced passageways across any linear barrier. Shortest-path trees also highlight routes that make critical barrier crossings.

To illustrate, Figures 11 and 12 show the shortest-path trees emanating from San José State University (SJSU) and from San José City College (SJCC) for LTS 2. They show the critical need for low-stress links extending west from the downtown area and extending southeast from SJCC. It is worth noting that there is no low-stress route connecting these two academic institutions.

This research does not propose a method for automatically identifying or optimizing needed network improvements; that task is left to planners. However, it does provide powerful methods for visualizing where improvements are needed, and – as discussed in the following sections of this report – for evaluating the connectivity impact of proposed improvements.

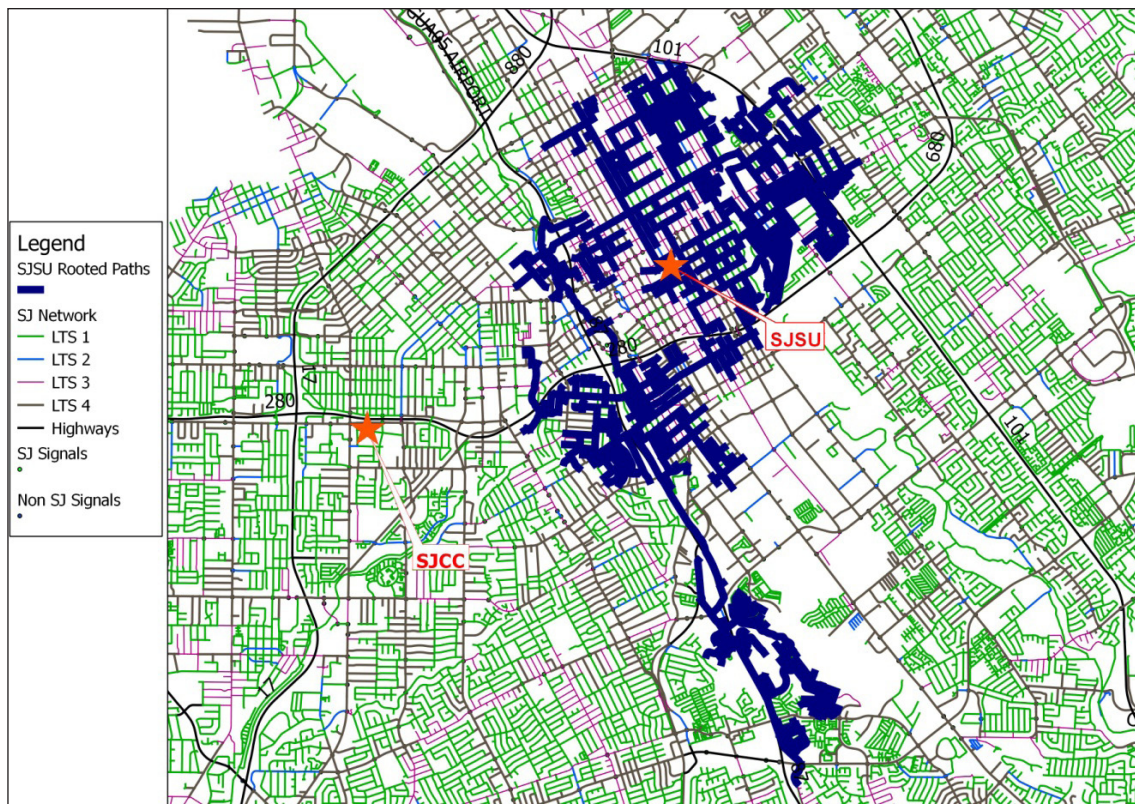


Figure 11. Shortest-Path Tree Rooted at San José State University, LTS = 2

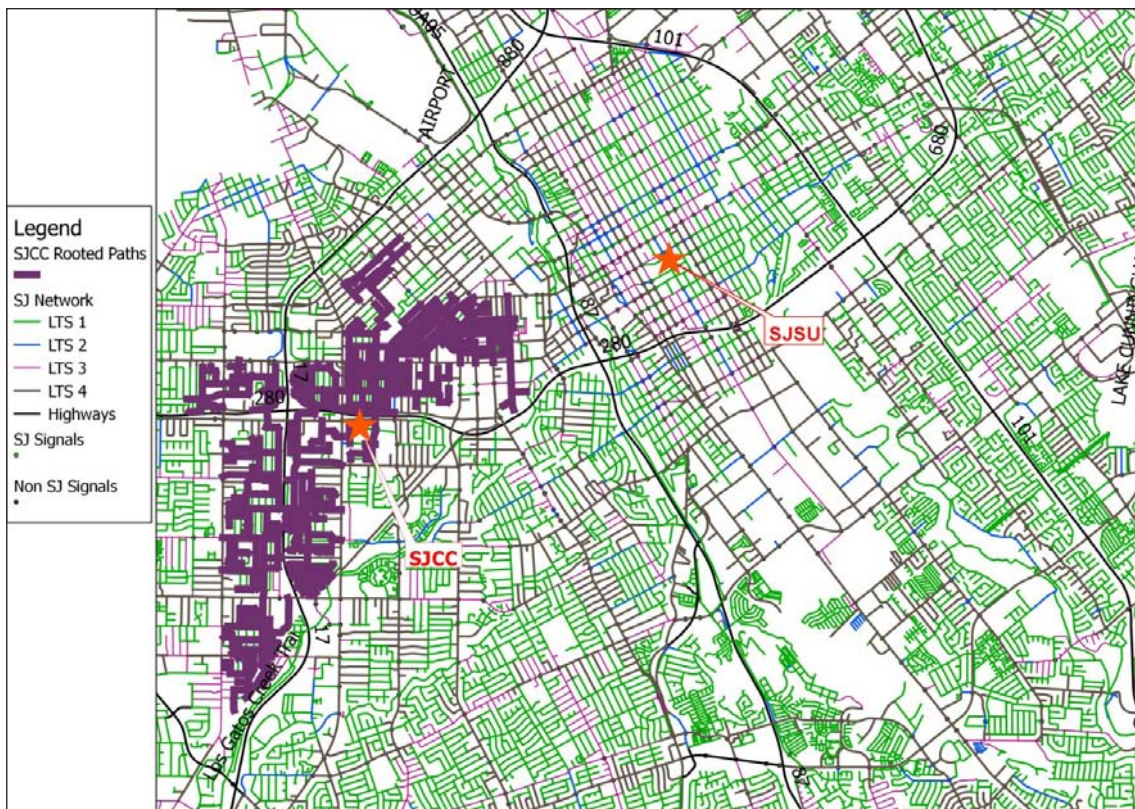


Figure 12. Shortest-Path Tree Rooted at San José City College, LTS = 2

VII. CENSUS BLOCKS AS GEOGRAPHICAL UNITS OF DEMAND

SHORTCOMINGS OF TRAFFIC ANALYSIS ZONES

Every trip has a starting and ending point. In conventional urban transportation analysis, demand points (points of origin and destination) are aggregated into traffic analysis zones or TAZs. TAZs are sized to have a population of about 3,000, and thus vary in size according to population density. In the San José study, there are 298 TAZs with an average population of 4,678. Their median area, 0.6 sq. mi., corresponds to a square whose sides are 0.78 mile long. In areas of dense non-residential development such as downtown, TAZs are only a little smaller; in San José, TAZs in the downtown have an average area of 0.47 sq. mile, corresponding to a square whose sides are 0.68 mile long.

The larger the geographical zone used for analysis, the smaller and simpler are problems of network analysis. The tradeoff is that large zones obscure the part of a trip at the origin and destination end that occurs within the zone of analysis. Urban transportation analysis usually treats all demand as though it is concentrated at the geographical *centroid* of its zone, and assumes that a zone's demand has access to the network via *centroid connectors* to vertices in the network that are either within or around the edge of the zone. For travel by automobile, obscuring the access route within a TAZ is usually inconsequential, since connectivity and travel time to access points varies little within a zone. For travel by transit, however, zone size can create large distortions, because the low speed of walking can make some parts of a zone accessible to a transit station while others are not. For this reason, we have championed the idea of using land parcels (in effect, individual buildings, and therefore the smallest meaningful geographic aggregation for transportation analysis) as units of demand when analyzing transit service.²⁵

With bicycling, the critical issue with zone size is not differences in distance or travel time, but rather differences in connectivity. A zone that is a residential "superblock" bounded by arterial streets, with no arterial streets passing through and with a well connected internal street grid would not present any significant distortion to bicycle network analysis. However, if the zone is traversed by a barrier (e.g., wide streets), or has an incomplete internal grid, some points in a zone may be accessible to the bicycling network via low-stress links while others are not. Locating all of the demand in such a zone at the zone centroid will either grossly under- or over-estimate the ability of demand points in that zone to connect to the network. A cursory examination of TAZs in the San José area reveals that there are many that lack the well connected, low-stress internal grid necessary to having uniform connectivity within the zone. Two examples are given in Figures 13 and 14. In Figure 13, a central arterial (McLaughlin Avenue) creates a barrier such that the western half of the TAZ has low-stress access to the Coyote Creek Trail, while the eastern half doesn't. Also, note how the incomplete street grid allows access to the streets in the northeast part of the TAZ via the east-west arterial (Tully Road) only. In Figure 14, note how a freeway (Highway 87) severs the TAZ so that only the east side has access to the Guadalupe Trail; also notice how on the west side, the only low-stress crossing of Pearl Street is near the zone's northern edge, forcing many would-be crossers to go out of their way.

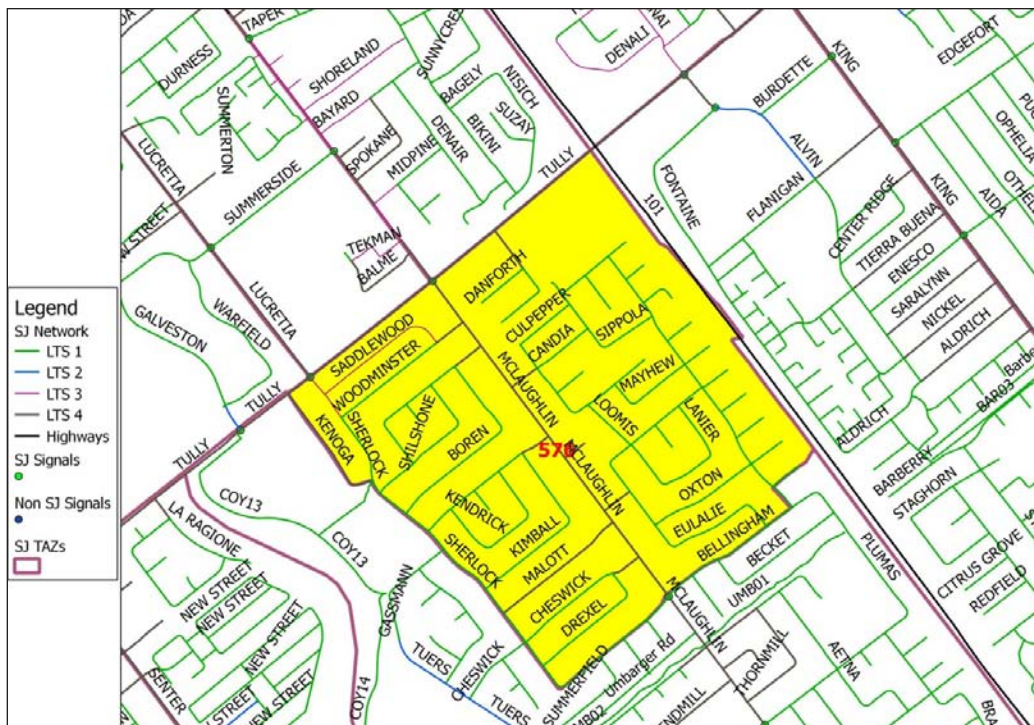


Figure 13. Traffic Analysis Zone Around McLaughlin Ave. Lacking a Connected, Low-Stress Internal Grid

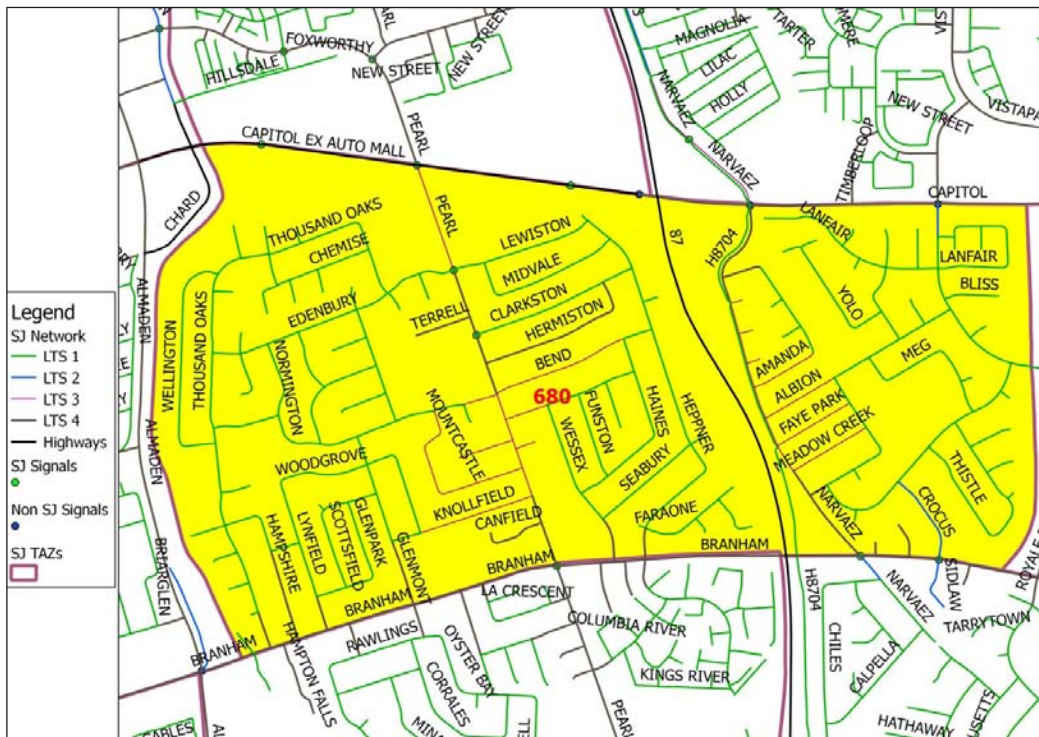


Figure 14. Traffic Analysis Zone Between Capitol Expressway and Branham Lacking a Connected, Low-Stress Internal Grid

BLOCK-TO-BLOCK DISTANCE MATRIX AND CONNECTIVITY

By performing shortest-path analysis on the subset of the street and path network whose links do not exceed a given level of traffic stress, the (shortest-path) distance from every vertex to every vertex was determined for every vertex pair at each level of traffic stress. This is the vertex-to-vertex distance matrix. Vertices that are not connected at lower stress levels were ignored. Hence there may be a vertex-to-vertex connection at stress levels 4 and 3 but they may not exist at levels 2 and 1.

To obtain the distance between any pair of blocks, we found the vertex on the perimeter of the origin block and the vertex on the perimeter of the destination block that, together with the length of their respective centroid connectors, yielded the minimum distance from the centroid of the origin block to the centroid of the destination block. Repeating for every block pair yielded the matrix of block-to-block travel times. This analysis was performed for each level of traffic stress.

DISAGGREGATING TAZ DEMAND TO THE BLOCK LEVEL

The matrix of demand by origin-destination pair is called a trip table. In the U.S., metropolitan planning organizations have created trip tables representing regional travel demand based on a combination of surveys and modeling work. Typically trip tables are created for different trip purposes (work, shopping, and so forth), and for both the present and a future year that represents the planning horizon. In the San José case study, we used the current-year trip table for work trips. In principle, trip tables for all trip purposes can be used.

Trip tables used for metropolitan transportation modeling use TAZs as their unit of demand. In order to use blocks as the demand unit, the demand in every TAZ had to be disaggregated to (allocated over) the blocks within the TAZ. Fortunately, TAZs are simple aggregations of census blocks.

Disaggregation was done at both the origin and destination end. Thus, for example, suppose for a given TAZ pair that the origin TAZ consists of 20 blocks and the destination TAZ consists of 30 blocks. Then the trips for that origin-destination (“O-D”) pair were distributed over 600 block pairs (20 x 30) by allocating origins over the 20 blocks in the origin TAZ and allocating destinations over the 30 blocks in the destination TAZ.

For work trips, the origin is usually a home. Therefore, origins were allocated over the blocks in an originating TAZ in proportion to their population. The U.S. Census freely publishes population by block.

Unfortunately, employment data is not measured by census block. To disaggregate destinations, we used a database of land parcels to calculate an “attraction strength” for every parcel, and aggregated attraction strength over the parcels belonging to each block to determine each block’s attraction strength. Trips destined for a TAZ were then allocated to blocks in proportion to the attraction strength of each block.

A parcel's attraction strength is the product of its size and a coefficient that reflects its trip attraction potential based on its land-use (e.g., office, light industrial, residential, etc.). This method of assigning a parcel's attraction strength was first used by Furth, Mekuria, and San Clemente (2007), using floor area as the measure of a parcel's size and attraction strength coefficients based on published trip attraction rates. Unfortunately, San José parcel data with actual land-use and floor area is not provided to the public (or to researchers) except at a high price; the only size measure available was a parcel's land area, and the only indication of land-use was zoning code. Strength coefficients were developed for almost 100 land-use codes, ranging in value from 3 for the core area to 0.01 for single-family residential with one-acre zoning. A set of sample coefficients is given in Table 10. While crude, this method has the desirable effect of allocating work trip destinations within a TAZ to blocks zoned commercial and industrial rather than to blocks zoned residential. Note that if all of the blocks in a TAZ have the same zoning, demand will be distributed uniformly over the zone (i.e., allocated to blocks in proportion to block area).

Table 10. Sample Attraction Strength Coefficients

Zoning Category	Attraction Strength per Acre
Core area	3
Commercial	1
Light industrial	0.5
Transit corridor residential	0.2
Low-density residential (5 dwelling units per acre)	0.025
Single-family (1 dwelling unit per acre)	0.01

VIII. SUMMARY MEASURES OF NETWORK CONNECTIVITY

The stress mapping tools described earlier offer powerful images that show a network's connectivity or lack thereof. Still, for evaluating progress or proposed improvements as a bicycling network is developed, it is valuable to have a numerical measure of connectivity. While graph theory offers several measures of connectivity, such as the ratio of the number of edges to the number of vertices, they are not related closely enough to network planning objectives to be of practical use.

The main objective of a bicycling network is to make it possible for people to get to where they want to go on a bike, using a route that doesn't exceed their tolerance for traffic stress, and without undue detour. Accordingly, this research proposes a summary measure of connectivity as follows:

Percent trips connected = fraction of trips in the regional trip table that are connected without exceeding a given level of traffic stress and without undue detour. Where demand is modeled at the block level, it is the fraction of block pairs that are connected, weighted by block-to-block demand.

Calculating percent trips connected requires using a trip table (a matrix of demand by origin-destination pair). After disaggregating demand to the block level, the analysis determines which O-D pairs are connected for a given level of traffic stress. Distance between every pair of blocks is determined from the vertex-to-vertex, shortest-path distance matrix with centroid connectors, as described earlier. For any block pair, comparing the distance at any given LTS to the distance at LTS 4 determines whether or not that block pair is connected (without undue detour). One simply sums the demand from the connected block pairs, and takes the ratio to the total demand.

An alternative measure of connectivity that requires neither a trip table nor a network analysis with block centroids but looks only at the connectivity between vertex pairs or node pairs:

Percent nodes connected = fraction of vertex pairs in the street and path network that are connected without exceeding a given level of traffic stress and without undue detour. This measure doesn't account for the relative importance of different O-D pairs, but is more readily calculated since it doesn't require a trip table or adding centroid connectors to blocks.

Percent nodes connected can be calculated directly from the street and path network without reference to demand or demand zones. By comparing the vertex-to-vertex, shortest-path distance matrix for a given level of traffic stress to the corresponding matrix at LTS 4, it can readily be determined which vertex pairs are not connected at all, are connected but with undue detour, and are connected without undue detour.

Percent trips connected is more difficult to calculate, but is more directly related to network planning objectives than is percent nodes connected, because it rewards you for connecting the points that people actually travel between. If trip patterns are widely scattered, there

should be little difference in relative value between the two measures; however, if people's trips tend to be concentrated on a small number of destinations (which is the case for work trips), then connectivity to those destinations will be given greater importance in the percent trips connected measure.

Because the appeal of bicycling as a valid alternative mode of transportation varies with distance, it may be meaningful to limit measures of connectivity to trips in a distance range appropriate to bicycling. An upper limit of 4, 6, or 8 miles on trips included in the calculation can be used to emphasize the bike network's potential to shift trips of moderate length to bicycling.

For very short trips, walking is more convenient than bicycling, so having good connectivity for very short trips is not likely to lead to more bicycling. If the regional trip table includes large number of people who work at home, their inclusion in measures of connectivity could significantly distort an analysis of the potential for people riding a bike to work. Therefore, in the San José case study, in lieu of applying a lower limit to distance, we excluded trips that began and ended in the same TAZ.

Where distance ranges are used, they refer to distance from an origin to a destination along the general street and path network. This means that the distance along a lower-stress path may be a bit longer than the nominal limit. This definition maintains fairness in comparisons between different levels of traffic stress in the sense of having the same membership in comparison groups.

IX. COMPARING BEFORE-AFTER CONNECTIVITY

In order to illustrate the use of the summary connectivity measures proposed in this research, they were measured for existing conditions in San José as well as for a scenario in which a slate of network improvements have been proposed.

PROPOSED SLATE OF IMPROVEMENTS

By examining stress maps and shortest-path trees rooted at key destinations, a slate of network improvements was proposed. The slate of improvements is mapped in Figure 16 and listed in Table 11. In keeping with the goal of attracting mainstream, traffic-intolerant cyclists, all of the proposed improvements reduce a link's level of traffic stress to 2 or lower.

The set of proposed improvements does not attempt to achieve any particular grid spacing and is far less ambitious than a complete network plan might be. It was selected to illustrate how a relatively modest set of improvements can bring about substantial gains in connectivity. The proposed improvements aim to create routes that cross barriers, connecting otherwise unconnected areas and leveraging the large existing masses of low-stress but disconnected streets. They are organized into 16 corridors, as shown in Table 11.

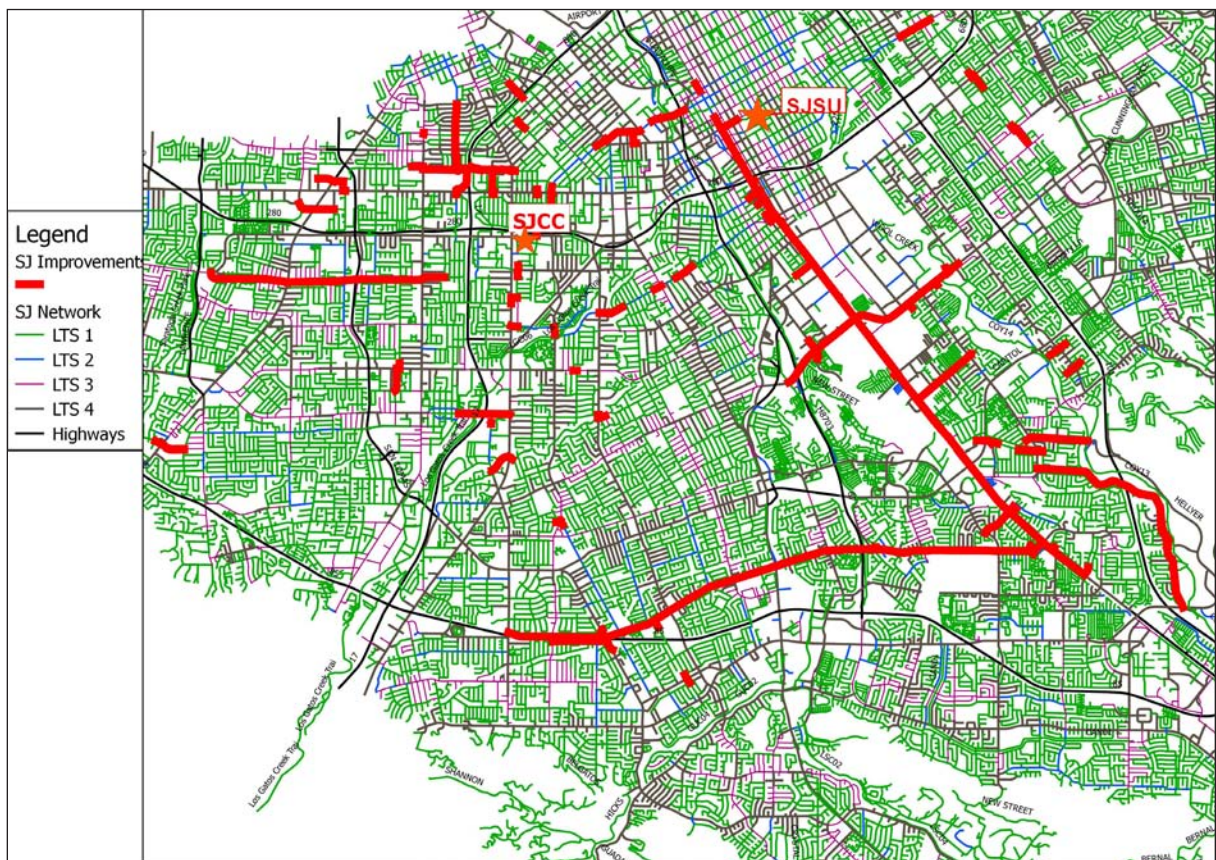


Figure 16. Location of Proposed Improvements

Table 11. Proposed Improvements

Street	Type ^a	LTS	Corridor	Street	Type ^a	LTS	Corridor
Julian	calm	2	Julian - Del Mar	Dry Creek	short	2	Campbell
Alameda	int	2	Julian - Del Mar	E. Campbell	int	1	Campbell
Hanchett	int	2	Julian - Del Mar	Meridian	int	1	Campbell
Del Mar	int	2	Julian - Del Mar	E. Campbell	CT	1	Campbell
Del Mar	int	2	Julian - Del Mar	Cox	int	2	Campbell
Stokes	int	2	Julian - Del Mar	Cox	int	2	Campbell
Leigh	short	1	Julian - Del Mar	Union	short	2	Ross
Hamilton	int	1	Hurst	Orange Grove	int	1	Ross
Willow	calm	2	Willow	Ross	int	2	Ross
Rhodes	int	2	Sunol	Humboldt	CT	1	Monterey
Alameda	int	2	Sunol	Second	CT	1	Monterey
Forest	CT	1	Forest	Monterey	CT	1	Monterey
Winchester	int	1	Forest	Rice	int	2	Monterey
Keystone	int	2	Forest	Skyway	short	2	Monterey
Keystone	int	2	Forest	Skyway	short	2	Monterey
Breech	int	2	Forest	Stonyhaven	int	1	Monterey
Stevens Creek	int	2	Forest	El Cajon	int	1	Monterey
Kiely	short	1	Forest	Seven Trees	int	1	Monterey
Kiely	short	1	Forest	Lewis Rd	calm	2	Monterey
Dana	int	2	Dana	Branham	short	1	Monterey
Dana	int	2	Dana	Branham	short	1	Monterey
Park	short	2	Dana	San Fernando	calm	2	Monterey
Park	short	2	Dana	1st St	calm	2	Monterey
N. Monroe	calm	2	Monroe	E. San Antonio	calm	2	Sunset
Monroe	int	2	Monroe	Sunset	int	1	Sunset
Winchester	int	1	Kenwood	Winterpark	int	1	Sunset
Leon	int	1	Williams	Hellyer	calm	2	Coyote
Bascom	int	1	Williams	Coyote Rd	calm	2	Coyote
Williams	calm	2	Williams	Alvernaz	int	2	Coyote
Belrose	int	1	MacArthur	Brandybuck	int	2	Coyote
MacArthur	int	1	MacArthur	Brandybuck	int	2	Coyote
Stevens Creek	int	1	MacArthur	Branham	calm	2	Branham
Hamilton	int	1	Cypress				
Eden	int	1	Cypress				
Milton	int	1	Cypress				

Note: ^a Type codes: calm = lower traffic speed and/or fewer travel lanes; CT = cycle track; int = intersection safety improvement, such as adding a median refuge island or signal; short = short section of shared-use path or cycle track.

Specific descriptions of how these improvements might be made are not given in this research because they are only illustrative. Nevertheless, the suggested improvements are all things that the authors, as traffic engineers and planners, consider plausible. They include 11 traffic calming projects (e.g., reducing the number of lanes on a road, adding bike lanes, lowering speed limits) that could be accomplished mainly by adjusting lane striping;

40 intersection improvement projects, such as adding a median refuge or reconfiguring right-turn lanes and pocket bike lanes; 11 short sections of connector pathways; as well as five cycle track projects that would entail considerable cost. The prevalence of intersection improvement projects highlights the important role that intersection design plays in creating or removing barriers to low-stress cycling.

RESULTS

With the proposed slate of improvements, many of the connectivity clusters at level of traffic stress 2 combine to form a single large cluster that includes the downtown and considerable areas south and west of the downtown, as shown in Figure 17. San José State University and San José City College become connected to each other at LTS 2 as well.

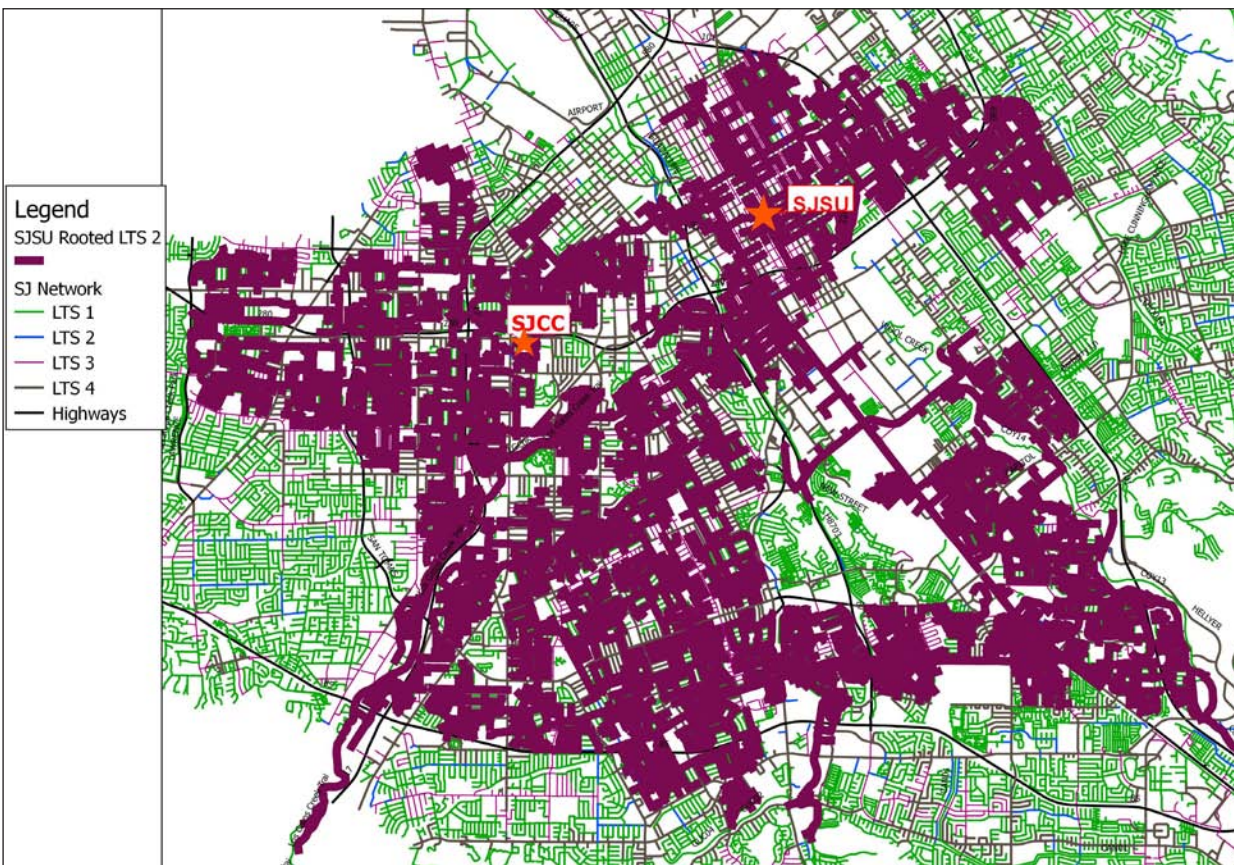


Figure 17. Connectivity Cluster at LTS 2 With the Proposed Slate of Improvements

However, within this cluster there are still many O-D pairs that are not connected because of the length of detour they require. For example, Figure 18 shows the shortest paths from Redondo Drive to the block of Grace Street just north of Hamilton at levels of traffic stress 2, 3, and 4. The most direct route, at LTS 4, uses Hamilton, a street with high level of traffic stress. The extra detour needed to follow a LTS 2 route (going north to Willow Street) makes the two endpoints disconnected at LTS 2. Even at LTS 3, the points are disconnected because the shortest path at LTS 3 (via Dry Creek) is so much longer than the most direct route.

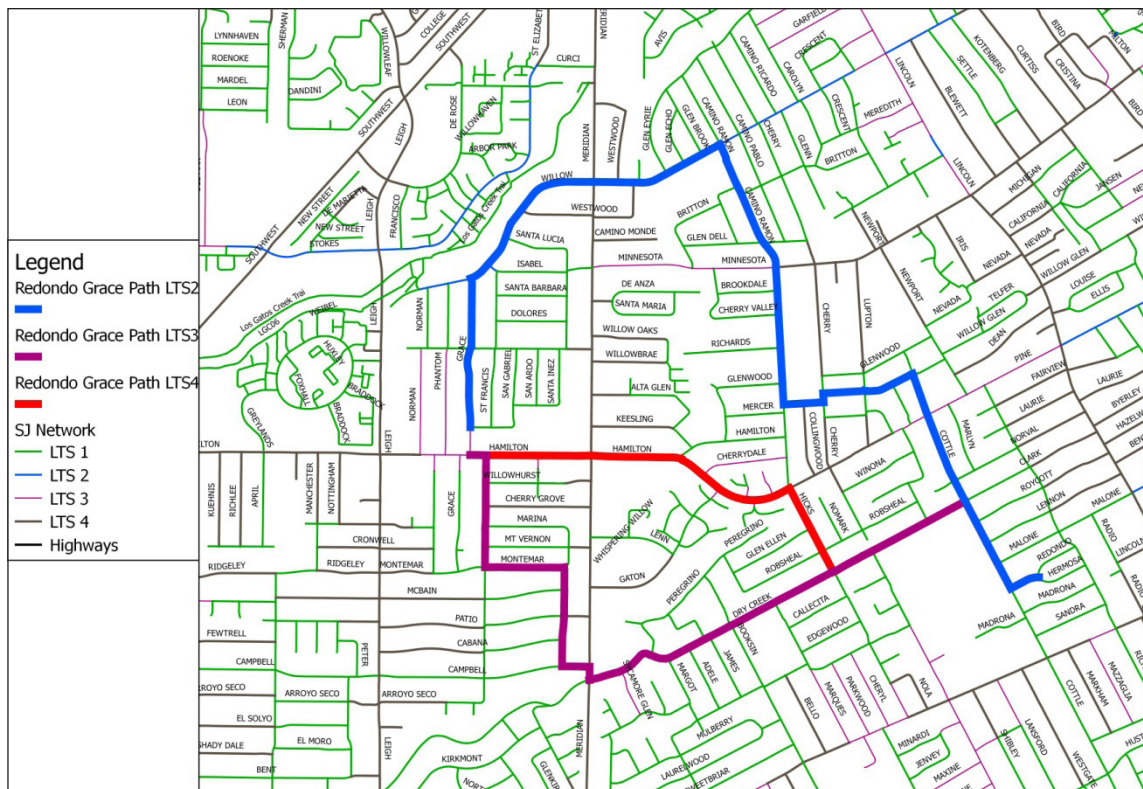


Figure 18. Paths from Redondo Drive to Grace St. at Levels of Traffic Stress 2, 3 and 4

Table 12 shows before-after comparisons in percent trips connected for different distance ranges as well as different levels of stress. Results for O-D pairs up to six miles apart are also presented in Figure 17. Poor connectivity at low-stress levels is clear in the base case, with only 0.4 percent of work trips up to six miles long connected at LTS 1, and only 4.7 percent connected at LTS 2. Under the improvement scenario, those figures rise to 1.0 percent and 12.7 percent, respectively, an increase by a factor of approximately 2.5. These results show how a well targeted set of network improvements can more than double connectivity, which can be seen as doubling trip-making potential.

Table 12. Fraction of Work Trips Connected at Different Levels of Traffic Stress

a. Existing Case

	Trip Length			
	< 4 mi	< 6 mi	< 8 mi	All
Stress Level 1	0.7 percent	0.4 percent	0.3 percent	0.2 percent
Stress Level 2	7.7 percent	4.7 percent	3.4 percent	2.2 percent
Stress Level 3	22.6 percent	16.4 percent	13.2 percent	8.9 percent
Stress Level 4	100.0 percent	100.0 percent	100.0 percent	100.0 percent
Total Trips	78,673	136,652	189,439	292,396

Note: Excludes intrazonal trips.

b. Improvement Scenario

	Trip Length			
	< 4 mi	< 6 mi	< 8 mi	All
Stress Level 1	1.7 percent	1.0 percent	0.8 percent	0.5 percent
Stress Level 2	14.9 percent	12.7 percent	11.1 percent	7.9 percent
Stress Level 3	27.4 percent	22.7 percent	20.0 percent	14.6 percent
Stress Level 4	100.0 percent	100.0 percent	100.0 percent	100.0 percent
Total trips	78,673	136,652	189,439	292,396

Note: Excludes intrazonal trips.

In the base case, the far greater connectivity at LTS 3 than at LTS 2 shows the important role played by links at LTS 3 in the existing network. It reflects the city’s past policy of emphasizing bike lanes on busy arterials, which represent the majority of the LTS 3 links. This policy can be contrasted with focusing network development on “bike boulevards” (routes using low-traffic streets, as seen extensively in Berkeley) or cycle tracks (separated bikeways). The difference between LTS 3 and LTS 4 is even greater, indicating that many barriers remain uncrossable except at a high level of traffic stress.

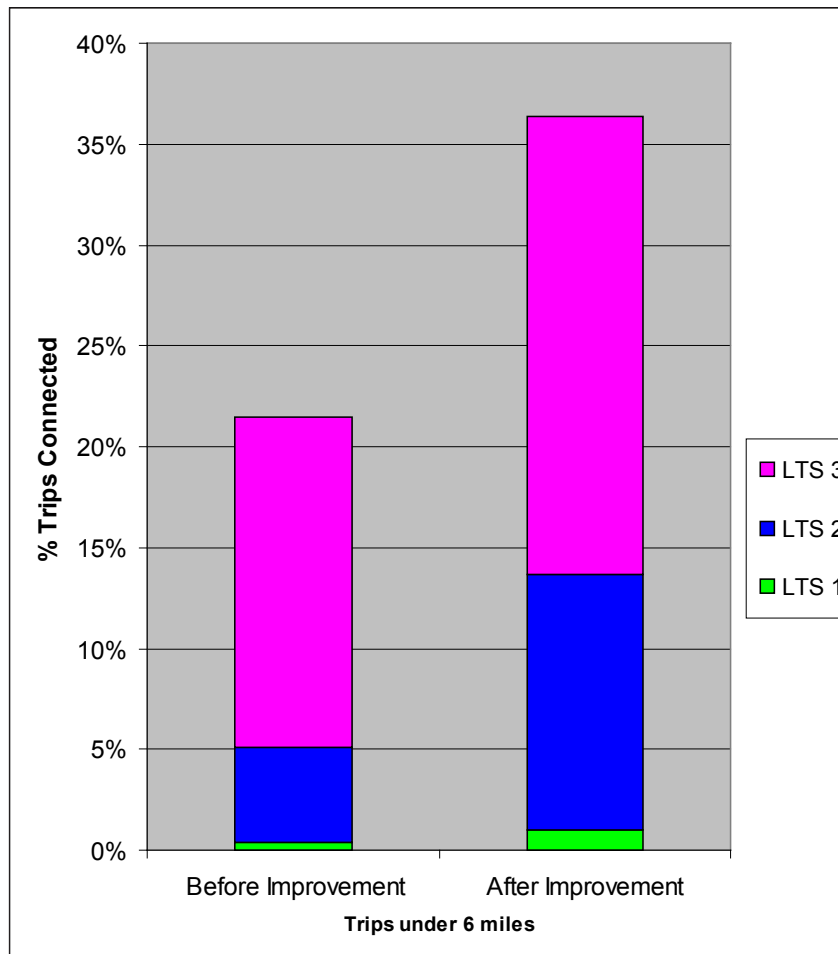


Figure 19. Fraction of Work Trips Up to Six Miles Long that are Connected at Different Levels of Traffic Stress

Results for percent nodes connected are shown in Table 13. For LTS 1 and LTS 2, the proposed improvements increase the fraction of vertex pairs that are connected about five-fold. The changes found in percent nodes connected are of the same order of magnitude as those found for percent trips connected; however, the differences are great enough that it does not appear sufficient to use the simpler measure in place of the demand-weighted measure.

Table 13. Changes in Percent Nodes Connected

Traffic Stress Level (LTS)	Existing	With Improvements	Ratio
1	803,026	3,764,267	4.7
2	987,598	5,735,602	5.8
3	7,906,045	11,751,470	1.5

X. DATA AND ANALYSIS ISSUES

This section reports on noteworthy issues related to data and analysis.

OMISSIONS AND ERRORS IN THE STREET AND PATH DATA FILES

Data files are bound to include some errors. Considering the focus of this research, we paid special attention to ensuring accuracy where it affected the network's connectivity at low levels of traffic stress.

Noteworthy omissions that were manually corrected included some newly constructed sections of trail, a footbridge (with bikable ramps) over a freeway, paths through college campuses, and several blocks of S. 7th Street that were inexplicably missing from the street network. Some of these omissions were detected by checking that all footbridges were included, others from examining low-stress, shortest-path trees and noting unusual barriers.

In some cases, trails didn't link properly to the street network, something that could be seen and corrected by zooming in. Such errors were detected by observing how low-stress routes failed to take advantage of those known connections.

A few errors in attribute data were also observed and corrected. For example, one block of a downtown street with two travel lanes and diagonal parking was coded as having five travel lanes. This error was detected when stress maps showed an inexplicable high-stress link on an otherwise low-stress street.

There are probably many more errors in attribute data that were not corrected. Most of them don't affect a street's level of traffic stress, and are therefore moot. However, there are probably some that do. Because the purpose of this study was to develop a methodology and proof-of-concept, it had neither the resources nor the mandate to ensure error-free data. The results reported in this study should be interpreted with this in mind; actual connectivity, in particular, may be different from what is reported. If a city publishes stress maps to advise cyclists of street conditions, or to develop and publish preferred routes, correcting errors would be more important.

Getting feedback from the public ("crowdsourcing") is probably the most effective means of detecting errors.²⁶ Crowdsourcing could also be a valuable means of calibrating level of traffic stress criteria.

MODELING ONE-WAY STREETS

The network analysis used treated streets as edges and not as directed arcs. That meant one-way streets could not be distinguished from two-way streets or by direction. San José has relatively few one-way streets except in the downtown grid where they usually appear as couplets offering identical levels of traffic stress and the same connectivity to cross streets.

However, in a few cases, the connectivity found by network analysis applies in only one direction because of one-way restrictions for which there is no comparable pair. One such case, a very important one in overall connectivity, is a 150-ft. one-way section of Almaden Blvd. along the east edge of Highway 87 that connects two sections of W. St. John St., one of the few streets offering a low-stress crossing of Highway 87 and Guadalupe Creek. Our connectivity measures assume that bikes can ride both ways along this link. (The City of San José plans to create a segregated bikeway along this link.)

One way to model one-way streets is to treat all road segments as arcs with specified directionality, and to use shortest-path analyses that account for directionality. The result could be that an origin-destination pair is connected while its opposite is not. However, this is an unsatisfying result. Most trips are round trips; if a person has a safe route to get to work, but not to get home, that person won't ride in either direction. Results could then be aggregated with a logic that considers an O-D pair connected only if its opposite is connected. A simpler, though somewhat arbitrary, solution is to close low-stress links (such as the W. St. John link mentioned above) that lack an opposite direction partner, and to raise the stress level of any pair of one-way streets to the level of the more stressful member of the pair.

SOFTWARE

This research made extensive use of the opensource Quantum GIS software for geographic modeling. Large datasets were manipulated using SQLite database software. Analysis routines were written in C++.

XI. CONCLUSIONS

Bicycling in America suffers from a lack of connected, low-stress routes that appeal to the mainstream, traffic-intolerant population. A method for measuring the ability of a bicycling network to meet that need can be a vital tool for network evaluation and development. Therefore, in order for bicycle network connectivity to be measured meaningfully from a user perspective, this research set out to develop and test a methodology for classifying segments and crossings according to their level of traffic stress, and to develop a methodology for determining the extent to which the trips that are made in today's travel patterns could be made on bike using low-stress links that appeal to the mainstream population without resorting to higher-stress links that are shunned by most people. These objectives were realized, with both methodologies demonstrated in a case study of San José.

The Level of Traffic Stress criteria developed and applied proved to be capable of distinguishing four levels of a road's or crossing's stressfulness, corresponding to identified user classes. The criteria proposed offer cities a way of mapping their bicycling networks according to which populations they serve rather than according to facility type. The concept is defined in such a way that criteria could be adjusted according to policy objectives or to reflect differing data availability.

This research has highlighted the importance of intersection approaches and street crossings in network connectivity. A major achievement has been developing criteria for crossing stress and a way of integrating intersection stress with the stress on a link.

This research tested the concept of disaggregating demand from standard traffic analysis zones to census blocks, which are much smaller geographic units. The rationale is that bicycling connectivity is often not uniform across those larger zones and that an accurate picture of connectivity therefore requires a smaller geographical unit of demand. We proved the feasibility of block-level disaggregation using a rather crude land-use database, as well as the feasibility of connecting blocks to vertices in the street network.

We developed several analysis tools for visualizing connectivity, including stress maps, shortest-path trees, and maps highlighting barriers and islands. Graphics from the case study poignantly illustrate the principles behind this research – a mix of low- and high-stress links, poor connectivity among the low-stress links, the critical role of intersection approaches and crossings in low-stress connectivity, different types of barriers, and isolated islands of low-stress cycling that result from a lack of connectivity.

We also developed two numerical measures for overall network connectivity – percent trips connected and percent nodes connected. We demonstrated the feasibility of measuring them for a rather large-scale area, the city of San José. This application successfully tested a proposed criterion for acceptable level of detour.

We demonstrated how a slate of network improvements aimed at providing critical, low-stress links is able to result in a dramatic increase in network connectivity. In this case

study, the proposed improvements increased the fraction of work trips that could be made on the subnetwork of low-stress streets and paths by a factor of 2.5.

Our network analyses used the entire street and trail network. One question that deserves attention in future research is whether these same or similar methods can be applied to a limited designated “bicycling network.” A high percentage of the street network is local streets that are used only for accessing the “real” through routes of the network, and it may be possible to capture the essence while omitting those access-only links. By including all local streets, the methodology we used, incidentally, can be used as a tool to identify “bike boulevard” routes, that is, routes using local streets that serve through bike traffic while not serving through motor traffic.

ABBREVIATIONS AND ACRONYMS

AASHTO	American Association of State Highway and Transportation Officials
BCI	Bicycle Compatibility Index
BLOS	Bicycle Level of Service
CROW	Official Name of the Dutch Publishing House for Infrastructure Construction References
GIS	Geographic Information System
FHWA	Federal Highway Administration
LTS	Level of Traffic Stress
NACTO	National Association of City Transportation Officials
O-D	Origin-Destination
TAZ	Transportation Analysis Zone
TRB	Transportation Research Board

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