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A feasibility study for a sustainable 21st century UCSC transportation system

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I. Introduction

Imagine a UCSC transportation system based entirely on electric, driverless vehicles. Imagine those vehicles responding to your immediate demand rather than circling periodically on their regular routes, crammed or empty, depending on the hour. Imagine travelling directly to your desired destinations rather than losing time at every bus stop. Imagine those EVs charged by solar photovoltaic carports over the East and West Remote parking lots. And imagine this new campus transportation system making a major contribution to required, state-mandated reductions in UCSC's greenhouse gas emissions (GHG). Difficult to imagine. Feasible? Yes. Improbable? Perhaps. Impossible? Not at all.

Under the terms of California's "cap and trade" program, all "entities" producing more than 25,000 metric tons of greenhouse gas emissions annually are required to reduce them by prescribed levels each year in the future. The state Air Resources Board is required to adopt regulations "to achieve the maximum technologically feasible and cost-effective GHG emission reductions [including] cleaner transportation."[1] By 2020, In the case of UCSC, under a business-as-usual scenario, campus emissions could exceed 100,000 MT/year, requiring major reductions in the face of considerable penalties. Because more than one-third of campus emissions are attributable to transportation (excluding air travel), significant reductions in that sector will be an important element in any broader GHG reduction strategy.

The state mandate to reduce emissions will require improved transportation modes and systems to meet regulations, which offers UCSC the opportunity to develop and deploy a 21st century transportation system, taking advantage of the best of new energy and transportation technologies, new hardware and software, and new forms of organization and piloting them on a peri-urban testbed. Already, many of these technologies are being tested and deployed, for example, at Stanford University, which has a substantial EV fleet. "On-demand" systems exist in many places, while driverless transit vehicles are also being tested for regular use.[2] With a firm commitment today by the UCSC administration, such a system could be in place by 2020.

This document is a feasibility study of various options for reconfiguring UCSC's transportation system. Given major uncertainties about technologies, costs and savings, this

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[1] Under "cap and trade," permitted quantities of greenhouse gas emissions decline each year, and emitters are allowed to trade permits in order to meet their individual requirements. For detailed information about AB32, see California Air Resources Board, "Assembly Bill 32 Overview," Aug. 5, 2014, at: http://www.arb.ca.gov/cc/ab32/ab32.htm (accessed 8/19/14) and California Air Resources Board, "First Update to the Climate Change Scoping Plan," Sacramento, CA, May 2014, at: http://www.arb.ca.gov/cc/scopingplan/2013_update/first_update_climate_change_scoping_plan.pdf (accessed 8/19/14).

[2] See references in the section 9.

study examines possibilities and alternatives rather than proposing concrete plans or objectives. But this report also offers some ideas about how those plans and objectives might be pursued, should UCSC decide to do so. A primary focus of this study is evaluation of those changes that could contribute most to GHG reductions and could create a model system to be emulated all over the world

We begin this study with a brief discussion of campus GHG emissions and the reductions required under California law. The second part of the study describes the current campus transportation system and its relationship to the surrounding community. We then turn to a focus on private vehicles and, in particular single occupancy vehicles (SOV), which represent the largest fraction of campus GHG emissions associated with transportation, and address how SOV trips could be reduced significantly through ride-sharing and "Direct-to-Campus Rapid Transit" (DCRT). We also consider specific rider demand, travel and destination issues, which are central to the design of a demand-response system. In the fourth section, we examine technological alternatives, including hybrid and electric buses, and autonomous vehicles. The study then evaluates how autonomous vehicles on campus could dovetail with a demand-response system. We conclude with our recommendations and propose a pilot program to be implemented on campus by 2017, and a full system by 2020.

II. Campus greenhouse gas emissions & targets

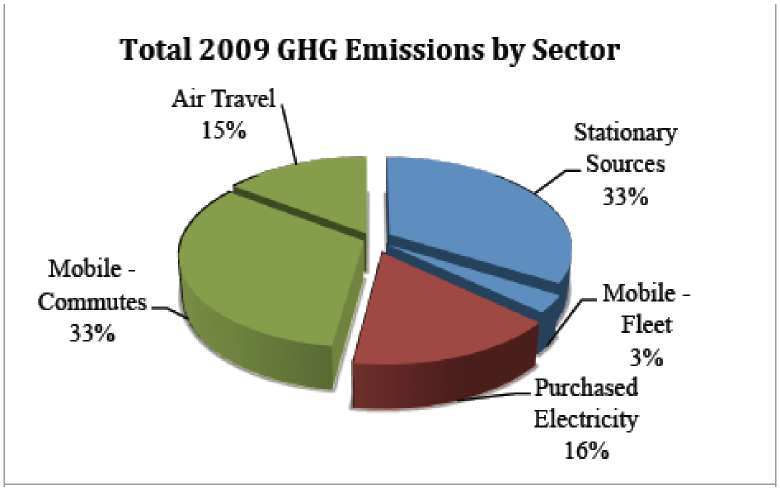
California's AB 32 law, the Global Warming Solutions Act of 2006, requires California to reduce its GHG emissions to 1990 levels by 2020, and 80% below 1990 levels by 2050. This mandate applies, in particular, to entities that emit more than 25,000 metric tons of carbon dioxide equivalent per year (CO2e). Depending on what one measures, and how, UCSC is subject to reporting and monitoring under the terms of AB 32. Failure to reduce GHG emissions by the required amount will result in considerable penalties over time.[3] AB 32 distinguishes among three emission sources: Direct, which come from mobile and stationary sources; Indirect, which come from purchased electricity, steam, heating and cooling; and Optional, which include employee commuting and business travel. Initially, at least, the campus is responsible only for reducing direct emissions under the state's cap-and-trade system. The other two types of sources will be addressed in the future.

Table 1 and Figure 1 illustrate campus GHG emissions from 1990 to 2013, while Table 2 shows some projections for the future (note that the projections in Table 2 are greater than current emissions) As is evident from the tables and figure, the vast majority of transportation-related emissions come from single occupancy vehicle commutes. Fleet emissions, which include campus buses, vans and other campus vehicles, are a mere 3% of total GHG emissions and only 6% of total transportation emissions. This means that electrification of fleet vehicles would directly reduce GHG emissions by a relatively small amount, although it could have other positive impacts, depending on the configuration deployed. For example, electrification could diminish current reliance on single occupancy vehicles (SOV) and *increase* demand for multiple-

[3] UCSC, "Climate Action Plan," Oct. 2011, at: http://rs.acupcc.org/site_media/uploads/cap/935-cap_2.pdf (accessed July 15, 2014).

occupancy vehicles (MOV), especially buses, by offering an improved transportation mode. Cleaner campus transportation paired with reduced reliance on SOVs would make a significant different.

Figure 1: UCSC GHG emissions, 2009, by sector



Source: UCSC, "Climate Action Plan," Oct. 2011, p. 7

Table 1: Historical GHG emissions by travel mode (in Metric tons of CO2e)

Year	SOV	Motor-cycles	MOV	Transit Bus	Fleet Subtotal	Non-Fleet Subtotal	Air Travel	Total
1990	18,443	211	5,891	247	*1,707*	24,792		26,499
2000	17,140	130	4,663	474	*1,741*	22,407		24,148
2007	15,782	145	4,800	759	*2,182*	21,487		23,668
2008	15,640	141	4,246	686	2,280	20,713		22,993
2009	14,747	143	4,554	1,184	2,195	20,628		22,823
2010	15,581	171	4,815	1,404	1,984	21,971		23,955
2011	15,181	183	4,457	962	2,112	20,784	3,585	22,896
2012	14,325	169	4,159	1,089	2,103	19,742	4,631	21,845
2013	13,531	158	3,989	1,066	2,032	18,745	5,299	20,777

Source: Pageler GHG model 2.2, Transportation & Parking Services, UCSC.

Table 2: Past, estimated and projected UCSC GHG emissions

UCSC Greenhouse Gas Inventory Summary (metric tons CO2e)						Business As Usual (Growth Adjusted Projections)			
						Low Estimate (CFP)		High Estimate (LRDP)	
Year	**1990**	**2000**	**2007***	**2008**	**2009**	**2014**	**2020**	**2014**	**2020**
Stationary Sources	16,989	19,681	22,872	24,081	24,046	24,101	25,181	27,622	32,834
Purchased Electricity	4,136	8,383	16,912	10,393	11,183	17,821	18,620	20,424	24,278
Mobile - Fleet	1,701	1,733	2,266	2,212	2,151	2,236	2,390	2,593	2,898
Mobile - Commutes	26,830	27,122	24,160	23,353	23,468	24,160	25,483	27,645	30,901
Air Travel	6,856	9,158	11,420	11,863	10,681	11,420	12,045	13,067	14,606
Totals	**56,512**	**66,077**	**77,630**	**71,902**	**71,529**	**79,768**	**83,720**	**91,351**	**105,519**

Source: UCSC, "Climate Action Plan," Oct. 2011, p. 3

III. UCSC travel patterns & current transit system

Rider population: There are approximately 17,000 enrolled undergraduates and graduate students at UCSC, almost 700 faculty and instructors, and 5,000 full or part-time staff members, for a total daily campus population of around 20,000. Approximately 7,500 undergrads and grads live in on-campus housing. They walk, ride bicycles and take both city and university vehicles to move around campus (some undetermined number also rely on SOVs to move around campus). Only a relatively small fraction of faculty and staff live on campus; of those, a small fraction use public and campus buses. For the purposes of this study, we assume that, on an average day, only 75% of the commuting university population is actually present (12,700)[4] on the main campus; we assume that the 7,500 students living on campus do not travel off campus. We also assume that the majority of the commuting population walk, bike, bus, carpool or travel in SOVs. The results of a one-day survey of commuter travel modes in 2013 are shown in Table 3; we estimate the total number of riders entering the campus to be around 14,000; adding the 7,500 campus residents suggests a daily campus population of approximately 21,500. Because some people enter the campus more than once a day, the estimate of 20,000 given above seems reasonably accurate.

On a daily basis, some 6,200 private vehicles (SOV & MOV) enter and exit UCSC, carrying about 7,900 riders (we exclude construction vehicles and motorcycles). Vanpools carry about 1,100 riders and the Santa Cruz Metro (SCMTD or "Metro"), 3,800. In 2012-13 (the latest year for which complete data were available for this study), the SCMTD carried almost 2.2 million student, faculty and staff to and from campus (Table 4). Typical ridership during a 30-day month, with 22 school days, is around 300,000 trips, which suggests a daily commuter ridership of around 5,750.[5] The modal survey, however, counts about 3,840 commuters daily. This implies almost 2,000 on-campus riders per day. According to the modal survey about 675

[4] Assumes 500 staff and faculty live in on-campus housing (including residential life staff).

[5] We assume ridership during the 8 weekend days is 6,000 trips, or a total of 48,000. That leaves 252,000 trips on the other 22 days, or 5,730 commuters per day.

commuters either bike or walk onto campus. We assume that the remaining 560 walk to the main entrance and catch a shuttle bus onto campus.

Table 3: Travel modes to and from campus, and number of riders

Travel mode	# of passenger trips	% of passenger trips	# of vehicle trips	% of vehicle trips	Est. # of commuters entering*
SOVs	9553	34%	9553	67.2%	4776
MOVs	6320	22.5%	2816	19.8%	3160
Motorcycles	279	1%	279	2%	140
Service/con-struction	746	2.7%	746	5.2%	373
SCMTD	7677	27.4%	340	2.4%	3838
Other TDM	2145	7.6%	483	3.4%	1072
Bicycles	1147	4.1%	0	0%	574
Pedestrians	206	0.7%	0	0%	103
Total trips	28073		14217		14036

*Rider commutes are two way; vehicle trips include both entries and exits.
Source: "Spring 2013 Multi-modal traffic survey," Transportation & Parking Services, UCSC. These numbers count vehicles heading in both directions.

Table 4: UCSC Student, Faculty & Staff SCMTD Ridership (2012-13)

Year	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	Total
Students	45525	43692	99823	324703	248092	117349	250183	249881	196910	281366	267437	122100	2058031
Faculty/ staff	13102	14433	13515	14106	11651	9135	11847	12225	12441	13042	13342	11136	108925
Total	58627	58125	113338	338809	259743	126484	262030	262106	209351	294408	280779	133246	2166956

Source: Annual SCMTD Worksheets, TAPS

How many riders travel by campus bus? The campus transit fleet consists of 20 buses, second-hand diesel buses purchased from San Jose and Sacramento. Campus buses provided almost 2,310,000 rider trips during academic year 2013-14 (Table 5). Taking again the 30 day month as a benchmark, and roughly 300,000 trips per month (and recognizing that the buses do not operate daytimes on Saturday and Sunday, and carry perhaps 1,000 riders each weekend evening), the daily TAPS load is about 13,275 passengers. The buses travel about 450,000 miles per academic year, on two routes (see below). We estimate 200 campus loops per day total in two directions (5 miles per loop) and 100 upper campus loops per day (3 miles per loop). The average number of trips per bus loop is therefore about 44 (due to multiple boarding and exits on each loop). As we show below, however, the number of trips per loop varies a great deal.

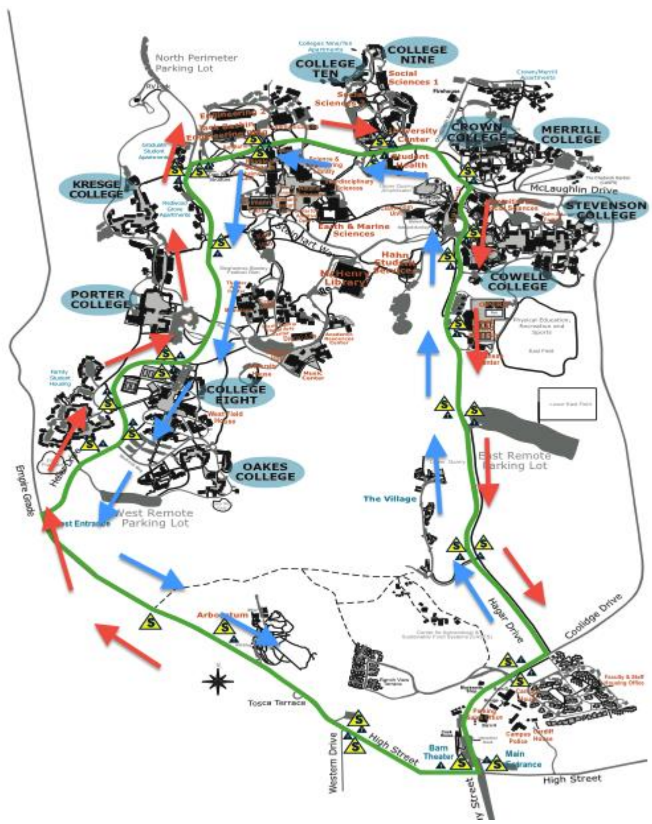
Table 5: Campus bus ridership, 2012-13 academic year

Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	March	Apr.	May	June	Total
72,656	374,304	259,153	104,869	**298,106**	288,307	177,109	**325,045**	**306,338**	104,066	2,309,953

Source: Transportation & Parking Services, "Shuttle Ridership WB.xlx. Feb. 14, 2014.

Routing & schedules: Currently, shuttle buses follow standard routes based on a fixed schedule, either on a 20-minute loop around campus or a 15-minute loop between East and West Remote parking lots (Figure 2). Metro buses run on fairly regular schedules throughout the day. Campus transit buses and Metro compete with private vehicles, pedestrians, bicycles and wildlife, which slow down traffic. During class periods, when there are few vehicles and pedestrians, the trip from the base of campus to Science Hill—a distance of about 2.5 miles—takes around 5-7 minutes; at peak times, the same trip can take as long as 15 minutes, with extended stops along the way to pick up and drop off riders. The success of a new TAPS program using students to direct traffic and pedestrian crossing provides strong evidence for the potential for altering campus traffic patterns. We have no data, however, showing whether this program reduces cross-campus travel time during peak hours.

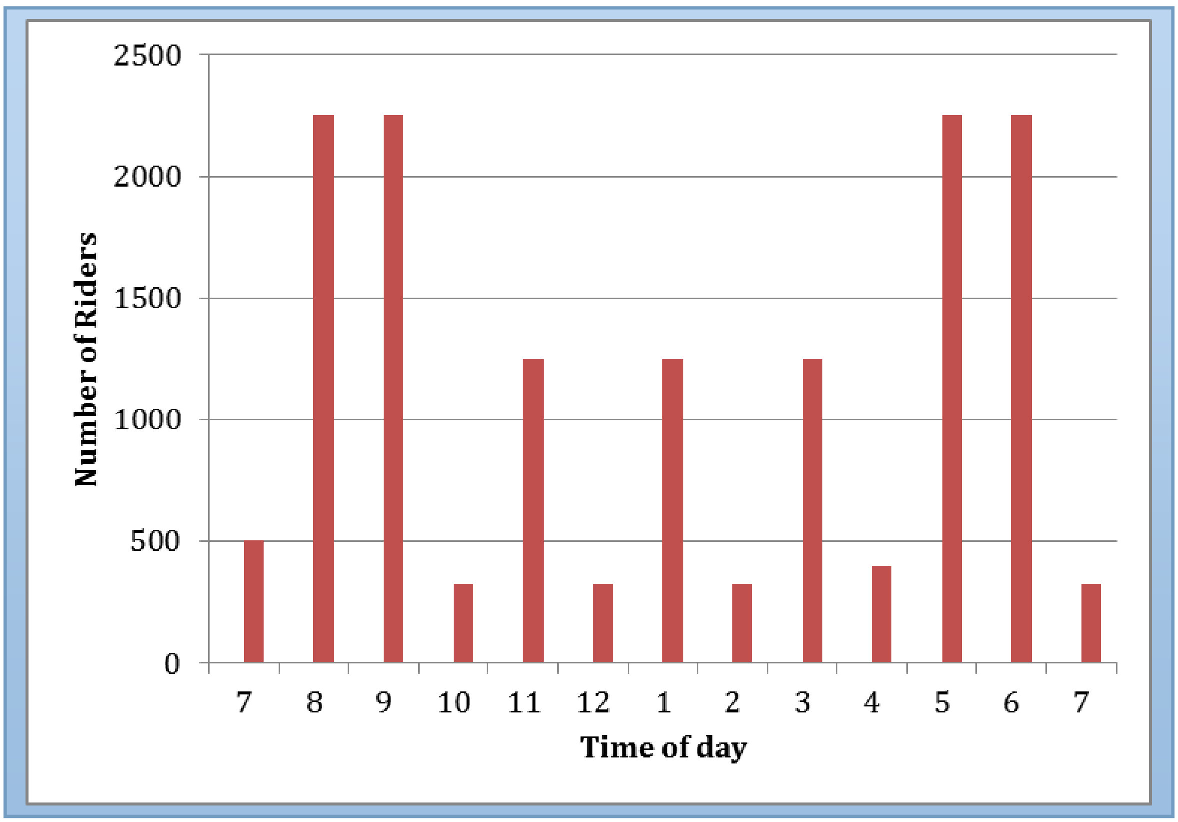
Figure 2: Campus bus route map



The Red Arrows indicate the Eastbound Loop Bus Route and the Blue Arrows indicate the Westbound Loop Bus Route.

The campus experiences several daily travel peaks, between classes, with two large daily ones, from 7-10 AM and 4-7 PM, as both staff and students arrive and depart (Figure 3). There are seven peaks on Monday-Wednesday-Friday; six peaks on Tuesday-Thursday). During periods of high demand, buses fill quickly near the beginning of their routes, making it difficult for riders closer to the center of campus to board them. The frequency of vehicles is increased during peak demand times, but even this extra supply is often insufficient to meet demand. Metro buses take up some of the excess, but students are discouraged from doing this, since it costs the University. Between the major peaks, ridership is much lower, and loop buses frequently carry only a few riders to off-campus and the Main Entrance stops. In addition, students often use Metro buses when the loop buses are running behind schedule—which costs the campus money each time a Metro fare is registered.

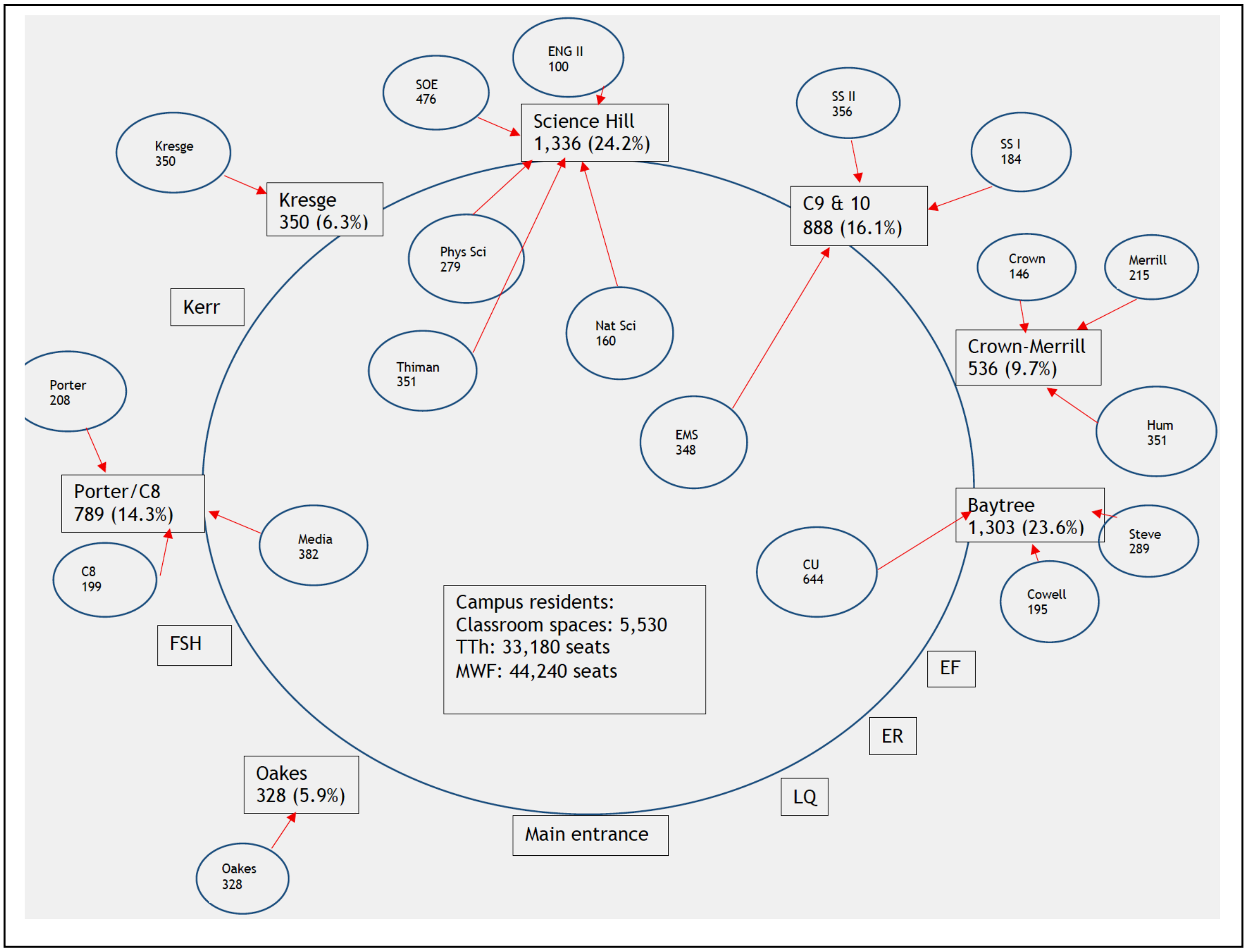
Figure 3: Example of TOD campus shuttle ridership



TOD ridership: We have developed a crude model of time-of-day ridership across the campus, based on the number, capacity and proximity of classrooms to bus stops (Figure 4) and conducted a TOD survey during Fall Quarter 2014 (full results can be found in the Appendix). We divide the campus into seven sectors, corresponding to individual bus stops (as indicated by red arrows in Figure 4).[6] We calculated classroom capacity surrounding each bus stop in order

[6] While the demand at the Main Entrance and Remote Parking Lots is considerable during peak times, we are interested in destination, rather than pickup, demand.

Figure 3: Campus classroom and hypothesized ridership distribution



to make a rough estimate of the "stock" of students that flows across campus during each peak. Not all of these students will use the transit system, of course, and not all students using the transit system are moving from one classroom to another. We also assume that, during the morning hours, demand peaks at the base of campus and the two remote lots; later in the day, demand at these three stops declines.

As evident from Figure 3—and for those who ride campus buses, from personal experience—the most "student classroom seats" are clustered around Baytree Plaza and Science Hill, although there is also a significant supply around the College 9 & 10 and Porter/College Eight stops. In estimating TOD rider demand, therefore, we have made three simplifying assumptions:

- during the day (8 AM-8PM), classrooms with a total capacity of 30 or more students are 65% full, while those with a capacity of less than 30 are 80% full;[7]

- 50% of the students in the vicinity of each stop will ride buses during peak hours; and

- between classes, demand varies but is a small fraction of peak demand.

Table 6 shows estimated TOD rider demand. To arrive at the numbers in Table 6, recall that we estimate the total number of daily trips on TAPS buses to be 13,275. Here is the calculation:

1. We assume that the base ridership across the day is 250 passengers/hour; over 12 hours, this adds up to 3,000 trips (1 rider = 1 trip).

2. We assume 3,000 additional trips in each direction (on-campus and off-campus) during the 2-hour morning and evening peaks, or 6,000 trips.

3. The remaining 3,675 trips are spread over the three smaller peaks, or about 1,225 additional riders, beginning 20 minutes before and lasting 5 minutes after class start times.

4. This last number is distributed among the 8-10 runs by buses (loop and upper campus) during each peak, or 120 trips per bus (although standing room only capacity of a bus is about 60, riders get on and off at various stops, so an individual trip will be shorter than a single bus run.

Table 6: Estimated TOD rider demand

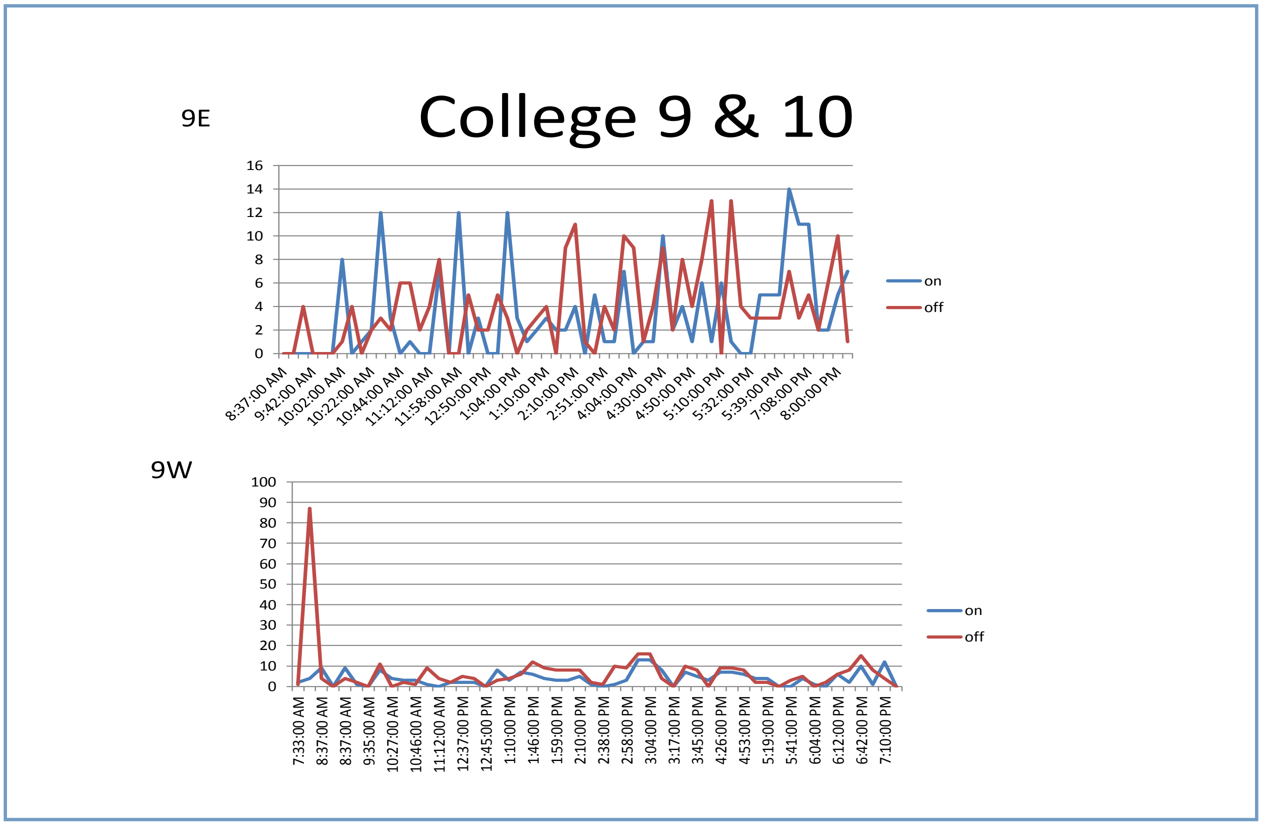
	# of class seats	% of class seats	7 AM	8 AM	9 AM	10 AM	11 AM	12 PM	1 PM	2 PM	3 PM	4 PM	5 PM	6 PM	7 PM	Total
Baytree	1303	23.6	118	437	437	59	295	59	295	59	295	118	437	437	88	
Crown-Mer	536	9.7	48	179	179	24	121	24	121	24	121	48	179	179	36	
Col 9-10	888	16.1	80	298	298	40	201	40	201	40	201	80	298	298	60	
Sci Hill	1336	24.2	121	448	448	60	302	60	302	60	302	121	448	448	91	
Kresge	350	6.3	32	117	117	16	79	16	79	16	79	32	117	117	24	
Porter-C8	789	14.3	72	265	265	36	179	36	179	36	179	72	265	265	54	
Oakes	328	5.9	30	109	109	15	74	15	74	15	74	30	109	109	22	
Totals	5530		500	1850	1850	250	1250	250	1250	250	1250	500	1850	1850	375	13,275

Source: Informational Technology Services, UCSC, "Classroom Support," at: http://its.ucsc.edu/classrooms/index.html (accessed June 30, 2014)

How does the model compare to the results of our survey? To collect the data, we had pairs of students ride loop and upper campus shuttles for an hour at a time and count students getting on and off at each stop. At peak times, loop shuttles run more frequently than off-peak, which means that the data do not give a complete picture of TOD demand at each stop. Figure 4 shows the pattern of rider boardings and exists at the College 9 and 10 stop. The graph clearly shows peak times, but it is not possible to compare these results with Table 6.

[7] Once the terms settles down, about 65-70% of enrolled students will attend large classes when there is no exam. The attendance rate is higher in smaller classes, since an absence is more likely to be noted.

Figure 4: TOD boardings and exits



IV. Redesigning the campus transportation system

The two primary goals of this study are to compare transportation alternatives in terms of cost, convenience and efficiency, to estimate the reductions on GHG emissions associated with each of these alternatives and to try to change the way students, staff and faculty approach transportation to, from and around campus. It is important to remember that, while GHG reduction might reduce overall system operating costs, this is not guaranteed. Moreover, if the operating cost of the reconfigured system, even including energy savings and avoided GHG penalties, is greater than the cost of a high-emissions path, it might not make economic sense to greatly modify the existing transportation system. Given UCSC's commitment to sustainability, it would seem that the campus should pursue the lower emissions path, but financial considerations generally play a central role in decision-making. We have attempted to address both goals without making a final judgment on which path to choose. The alternatives changes and reconfigurations discussed in this study are described briefly below, with greater detail in subsequent sections. They are listed in descending order of GHG reductions, not necessarily in response to California requirements under AB32.

- **Reduce the numbers of or even ban private vehicles from campus.** Because the greatest volume of GHG emissions originate with private vehicles, this policy, based on a combination of incentives and disincentives, has the greatest potential to reduce emissions.

- **Implement a countywide rideshare program, "Slug Line!" perhaps in partnership with the City of Santa Cruz, to encourage a shift to MOVs.** Companies such as Uber, Lyft and others are developing ridesharing programs around the world. If every SOV entering campus carried two people, GHG emissions from commutes could be reduced by 50%.

- **Develop a "Direct-to-Campus Rapid Transit" (DCRT) system for UCSC affiliates traveling to and from campus.** During periods of high demand, such buses would run along regular routes with set pickup points, which would ensure shorter travel times, eliminate the need to change buses and reduce loads on Metro lines to campus.

- **Run "express" and "local" bus services across the campus.** At present, all campus bus routes are "local" and buses stop on demand for boarding and alighting. Express buses traveling non-stop between heavily-used stops could increase bus speeds and bus supply, decrease travel times and reduce GHG emissions by eliminating starts and stops. Shuttle buses could also be scheduled to start from high-demand stops other than at the Main Entrance and in the Remote parking lots

- **Implement a demand-response transit system with variously-sized vehicles**. A demand-response system dispatches vehicles directly to locations at which riders wish to be picked up (much like a taxi dispatch system). On campus, this could be done with vans, rather than buses, especially during off-peak hours**.**

- **Replace the existing fleet with electric hybrid or all-electric vehicles**. The technology for both is well developed and has been tested extensively. Hybrids work better on hilly terrain and can operate with regenerative charging; electric vehicles are "emission free," although they may have difficulty climbing the hills without boosters and there may be emissions associated with electricity generation at the power plant.

- **Deploy autonomous vehicles (AV).** For better or worse, a major cost for any transit system is the labor of vehicle operators. AVs would reduce labor costs and, in combination with a demand response system, could also increase the efficiency of vehicle use.

These are not the only changes that could be made in the campus transit system, but others are likely to be more complicated, more expensive and more objectionable to some (e.g., gondolas from downtown, off-grade personal rapid transit, etc.)

V. Limit or ban entry of private autos to the campus

As noted earlier, mobile commutes by private vehicles comprise one-third of UCSC's greenhouse gas emissions. Single-occupant vehicles (SOV) account for 67% of campus traffic; adding in MOVs raises that to 87% (see Table 3). By contrast, the Metro carries almost as many passengers but represents only 2.4% of vehicular traffic. The single most effective reduction in GHGs would result from reductions in the numbers of SOVs and MOVs entering the campus. This could be accomplished in several ways. Limits or bans on private travel would impose costs on drivers and incur stiff resistance, especially since, without adding more buses to campus routes, the Metro could not cope with the resulting increase in peak loads. A second approach relies on raising the cost of parking permits, which would probably prove unacceptable to drivers, especially faculty and staff, unless an equally convenient alternative, such as ridesharing, were on offer. In addition, TAPS receives substantial revenue from sale of parking permits, part of which supports the bus system; those revenues would need to be replaced.[8]

Table 7 shows the number of parking permits issued to private vehicles, by category (data from 2011-12). Recall that the modal survey found that 7,900 private vehicles enter the campus on a daily basis. Based on the permit numbers in Table 6, we estimate that 6,365 private vehicles park on campus daily. We cannot account for the difference of 1,600 vehicles between the two numbers.

Table 7: Parking permits issued by TAPS in 2011-12

	Annual & quarterly	Scratchoffs	Temporary	Revenues
A,R,N (staff & visitors)	1,229	1,185	25,720	
A (all types)				$1,27,2044
MC	191		437	40,538
B & N (students)	558	780	2522	189,565
C,R,NC (undergrads)	3,123	555	13,521	1,726,015
Total	5,101	94,500 days*	126,600 days**	$3,228,162
Daily total parked	5,100	540	725	6,365 /day

Source: Andrew Klein & Larry Pageler, "Summary of Annual TAPS Parking Permit Sales," June 10, 2013.
* Assumes even split between 25 and 50 scratchoffs, and a school year of 175 days.
**Assumes even distribution among 1-5 day permits; total reflects the sum of each group (8,440 days of parking; 16880 days of parking. This probably overestimates the number of days of parking with temporary permits.

Table 8 lists the number and occupancy of parking spaces in the eight largest lots on campus, the results of a one-day survey (we estimate smaller lots to comprise 20% of total spaces on campus). Comparison of the number of single occupancy autos entering the campus, the number of permits issued, and parking space usage suggests that, on an average day, many

[8] Most, if not all, public transit systems cannot cover the cost of transporting a rider from passenger fares, and operate at a "loss." Generally, the difference is made up by some sort of subsidy.

vehicles are on campus only part of the day and/or make more than one trip to and from campus.

Table 8: Results of a one-day parking occupancy survey

Location	# of spaces	Average # of spaces occupied	Total daily # of vehicles parked
Hahn student service	151	133	184
East Remote	956	748	959
Crown College	131	73	159
Core West	433	358	497
Performing Arts	157	125	194
West Remote	287	286	288
North Remote	106	105	110
Oakes/College Eight	121	79	145
Total for these lots	2342	1907	2536
Other lots	1250	1020	1100
Campus total	3590	2927	~3635

Source: TAPS, "Parking Survey day 2013"

Annually, private vehicles entering and exiting UCSC emit about 17,500 metric tons of carbon dioxide. Hence, a significant reduction in private vehicle use could reduce emissions considerably. As Table 7 indicates, however, parking permit sales raise about $3,225,000 per year for TAPS, a not-insignificant fraction of its annual budget of $10,122,650 in 2014 (much of the remainder comes from student transportation fees). Halving the number of private vehicles would reduce TAPS income by about $1,600,000, which would affect campus bus service, which is subsidized by permit and student fees. Could this loss be recouped? Here we consider several alternatives: doubling permit costs; imposing GHG emission fees; and auctioning or leasing parking spaces.

- **Doubling permit costs**: We have no clear sense of the elasticity of demand for parking permits. At present, daily permit parking on campus runs from $2 to $4, depending on the type of permit (a temporary daily permit costs $6, meter parking is $1.50 per hour); a price increase would probably result in sale of fewer student permits, although doubling permit costs without consideration of financial ability to pay would discriminate against low-paid staff and low-income students.

- **Imposing GHG emission fees:** Current estimates of the social cost of carbon range between $14.30 and $67.10 per metric ton[9] (which is not the same as the current price of a CO_2 emission permit, which was $11.87 in California on August 15, 2014[10]). The total *social* value of emission fees at 50% of current private vehicle emissions (8,750 MT) is approximately in the range of $125,000 to $585,000, which would not compensate TAPS for the loss of revenues and add only about 20 to $1.06 per day to the cost of a daily parking permit (averaged over 3,150 cars entering the campus daily), which is hardly likely to deter private vehicles from entering campus.

- **Auctioning or leasing parking spaces:** Parking permits represent a license to "hunt" for a space; they do not guarantee a space. Might some drivers be willing to pay more for a guaranteed space, through an auction or lease agreement? What is the marginal value of a parking space? What if spaces were auctioned off or leased to drivers on an annual basis, thereby guaranteeing drivers a space? Here, the difficulty is that open spaces are frequently available across campus; the effective "leasing" cost of a space is currently equal to the annual cost of a permit (presently $520-$790 on an annual basis). This is almost surely too low: a one-day A permit costs $6; over a 175 day academic year, the annual cost of such parking would be $1,050. Assuming this to be an equilibrium "leasing" price, and that the number of parked cars is 50% of the 6,300 private vehicles entering campus, annual revenues raised would total $3,300,000, which achieves the same end as doubling permit prices. To avoid permit shock, TAPS could experiment with gradual increases in permit fees and determine at what price the number sold begins to decline.

As we suggest in the next section, ridesharing could reduce the impact of higher permit prices, especially with the appropriate incentive structure built in.

V. Carpooling and Ridesharing

The fact that more than 6,000 private vehicles enter campus every weekday, of which two-thirds are SOVs, suggests that an equal or greater number of passenger seats are available (we have assumed that each MOV carries a driver and one passenger, although the actual number of MOV occupants is 2.24). If even half of those vehicles were to carry one additional rider, greenhouse gas emissions from private vehicles and associated emissions would drop by more than 6,000 MT per year. What would be required to accomplish this goal?
Drivers choose to go solo for several reasons:

- Public transportation is inconvenient, slow and often crowded;
- Those living near campus are often passed by full SCMTD buses;

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[9] U.S. Environmental Protection Agency, "The Social Cost of Carbon," at: http://www.epa.gov/climatechange/EPAactivities/economics/scc.html (accessed 7/20/14).
[10] Climate Policy Initiative, "California Carbon Dashboard," at: http://calcarbondash.org/ (accessed 8/22/14).

- Individuals' hours on campus are irregular and don't fit with carpool or vanpool schedules;
- It is more pleasant to travel alone;
- The cost of driving and parking are relatively low.

These are not insuperable obstacles to encouraging ridesharing, especially if financial incentives can be built in to such arrangements.[11] An organized, on-demand ride-sharing system restricted to UCSC affiliates, could address at least three of these preferences: convenience, hours and cost. Ride-sharing is hardly a new idea but it has long been hampered by the difficulties in determining cost of acquiring short-term information: how does a potential rider find out who is going in the direction at the time s/he desires?[12]

Most riders are familiar with carpools, if only from their K-12 experience. Carpooling reduces transaction costs but binds the rider to a fixed schedule and loss of flexibility. Moreover, the UCSC carpooling system offers significant incentives to those who share rides to campus, but penalizes potential riders who don't own a car.[13] Carpool permit rules require that each rider (up to four) own and register his/her vehicle with TAPS. Like the three mythical Greae, aged sisters who shared a single eyeball and tooth among them, a carpooling group receives one permit whose cost is split among the group's members and that must be shared among them. No car, no carpool. Table 9 provides data about carpool permits: cost, cost per member, and the number of permits issued in 2011-12. The table also shows our estimate of the number of riders traveling daily in carpools: a maximum of around 2,500, compared to the 14,000 people who come to campus every day.

Could the number of carpools be increased? One possibility is to allow people who do not own vehicles to join carpools by paying for a share of the permit. On a daily basis, the cost of a ride would be less than 50 cents each way. Another would be to greatly increase the cost of individual permits relative to carpool permits. Without further study, however, we cannot estimate what effect either of these would have on carpooling and ridership. A third alternative is to provide financial incentives to SOV drivers to take passengers through a ridesharing program. This incentive would bring down the driver's permit cost without reducing TAPS revenue.

UCSC is a subscriber to Zimride (http://zimride.ucsc.edu), a third-party platform created by the founders of Lyft. Zimride is described as a ridesharing service but is, strictly speaking, closer to a bulletin board for casual carpooling. Zimride registers both drivers and passengers, their commuting schedules, and the fare asked by a driver or offered by a rider, for a shared ride to and from campus. Inspection of the site suggests that it is not heavily used: many postings are

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[11] For many years, the University provided free SCMTD passes to faculty and staff. There are no data showing whether the current bus pass cost of $10/month discourages their use.
[12] Hitchhiking is one way to reduce such transaction costs, but it suffers from drivers' concerns about problems of safety and status. Another possibility is to exchange information in classes.
[13] http://taps.ucsc.edu/parking/carpool-permits.html

Table 9: UCSC carpool permit costs, number issued and riders

Type of permit	Annual Cost (2014-15)	Cost per rider (assuming 4)	Number issued in 2011-12	Number of rides per day*
A carpool (faculty & staff only)	$570	$142.50	245	980
B carpool (graduate students only)	$570	$142.50	76	304
C carpool (students)	$390	$97.50	46	184
R carpool (students)	$474	$118.50	47	188
A carpool scratchoffs (50 daily permits)	$158	$39.50	168	672
B carpool scratchoffs (50 daily permits)	$158	$39.50	56	224
R carpool scratchoffs (25 daily permits)	$90	$22.50	data not available	data not available
Total vehicle trips/day				638
Total riders/day				2,552

Source: "Carpool Information and Permits, http://taps.ucsc.edu/parking/carpool-permits.html; TAPS Permit & Revenue Sheets, 2011-12.
* Assumes four riders per car per day.

made by people who commute on a regular basis from the San Francisco Bay Area to UCSC, although there is a fair supply of local rides (generally from origin points of about 15 miles from campus). The going rate for a local ride is about $4/trip; the cost rises with distance. There are no cumulative data available for ridership, so it is difficult to judge whether Zimride has made much impact on private vehicular traffic into campus. Many universities have either created ridesharing programs or collaborate with public authorities and private companies to offer transportation. Most of these are similar to Zimride and require matching in advance; there do not appear to be any that offer real-time, on demand ridesharing.

A real-time, ridesharing service matches immediate or short-term supply and demand: Riders seeking transportation post their location and destination via a smartphone app and matched with a driver, who may be headed in the desired direction or who are simply looking to earn some money.[14] Riders pay a price based on distance traveled, either via credit cards or electronic accounts. Lyft, Uber and Sidecar are commercial services that operate on the assumption that demand will generate supply.[15] Carma (https://carmacarpool.com/) is a national, carpool-like, ridesharing service that tries to match supply and demand. Drivers and riders post their travel plans via a smartphone app and make their own arrangements for pickup and dropoff. Drivers are paid a fixed cost per mile. Other ridesharing programs let drivers set prices for passengers. But such real-time services have a very short shelf-life if

[14] Nelson D. Chan & Susan A. Shaheen, "Ridesharing in North America: Past, Present, and Future," *Transport Reviews*39, #1 (Jan. 2012): 93-112.

[15] Carolyn Said, "Uber, Lyft, Sidecar try carpool service," *San Francisco Chronicle*, Aug. 7, 2014, at: http://www.sfchronicle.com/technology/article/Uber-Lyft-Sidecar-try-carpool-service-5672983.php (accessed Aug. 7, 2014).

commuting is involved: when drivers are ready to go, they go, and riders either join or are left behind.[16]

What would a well-designed, robust University-operated ridesharing program look like (let's call it "Slug Line!")? First, it would need to be pro-active in matching drivers and passengers and, second it would have to offer significant incentives to induce drivers and passengers to use Slug Line! (it is also important that ridesharing not draw drivers and riders away from the Metro. Slug Line! should be easy to use, available on a variety of platforms and restricted to members of the UCSC community (requiring a login with either a Blue or Gold id). It would operate along the following lines:

1. Both drivers and passengers register their vehicles with the University (those without cars must travel on the Metro), are vetted as staff, faculty or student, and provided with a secure identification code to be shown on demand by either driver or passenger (or both);

2. Drivers register their regular routes on the UCSCride website and app (only routes to and from campus routes are eligible to participate) and their commuting schedules;

3. Riders can either sign up with a driver in advance and arrange a pickup site, or match a real-time pickup with a driver; the driver is then notified that a passenger is waiting at a pickup site (these should be sites authorized by the University and local governments, and not bus stops);

4. Riders and drivers create payment and deposit accounts on UCSCride, linked to debit-type cards. For each ride on a particular driver's route, a fixed sum based on distance (e.g., $2 per round trip) is transferred from the rider's to the driver's account;

5. At the end of each academic year, when new parking permits are issued, the accumulated sum is either available to the driver on a debit card, or credited toward a parking permit for the following year (more passengers carried means greater year-end benefits).

How would this system look in action? Assume a driver makes 150 round trips (300 one way trips) driver per year, carrying one passenger paying $2 per trip. Over the academic year, the driver would earn $600, more than the cost of an individual R permit. Because each individual

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[16] There are numerous modeling studies of ridesharing available (e.g., Sevgi Erdoğan, Cinzia Cirillo & Jean-Michel Tremblay, "Ridesharing as a Green Commute Alternative: A Campus Case Study," *International Journal of Sustainable Transportation* (forthcoming), at: https://www.researchgate.net/publication/262337478_Ridesharing_as_a_Green_Commute_Alternative_A_Campus_Case_Study (accessed 8/8/14)), but few if any of them actually report on empirical results from actual ridesharing services (but see, e.g., Blerim Cici, et al., "Assessing the Potential of Ride-Sharing Using Mobile and Social Data: A Tale of Four Cities," *arXiv preprint arXiv:1305.3876* (2013), at: http://submission.netcod2012.org/lib/exe/fetch.php/public:assessing_potential_of_ride_sharing.pdf (accessed 8/8/14). A general observation in the literature is that ridesharing proposals and programs have been around since the 1970s, but have never really taken off, presumably due to the high transaction costs of exchanging demand-destination information. Smartphones, it is hoped, will provide rapid, real-time feedback to both drivers and riders.

who does not drive to campus results in a loss of $400-575 to TAPS, the system needs to be made revenue neutral. It makes sense, therefore, to raise the price of annual permits. This will reduce SOV use directly and will provide incentives for drivers to carry more passengers.

For every reduction of 1,000 vehicles entering campus, TAPS will suffer an incremental annual loss $400,000 to $575,000 (Table 10). Reducing the number of SOVs entering campus by 2,000, for example, would require raising permit prices to $667-958. To increase the number of passengers per (former) SOV to 2.5 would require raising permit prices to $1,000-1,438 (this does not take into account price elasticities; some drivers may prefer to pay the full permit price to drive alone). If we next assume that each passenger pays a driver $2 per day ($1 each way), what would be the net cost of a permit after deducting accumulated fares from the retail cost of a permit? The table suggests that, from the driver's point of view, the "sweet spot" is 1.5 passengers per day (this means some commutes without riders). From an emissions reduction point of view, the maximum reduction is most desirable. Note that the cost to the University of these reductions arises only from setting up the ridesharing system and administrative costs required to run it.

Table10: Impacts for UCSC of different degrees of ride-sharing

# of SOVs	# of SOV ex-drivers	# of people per vehicle	Annual GHG reduction*	Revenue loss to TAPS**	Permit price required to make up loss
5,000	**0**	**1**	**0**	**0**	**NA**
4,000	**1,000**	**1.25**	**2,700**	**$400-575k**	**$500-719**
3,000	**2,000**	**1.5**	**5,400**	**$800-1,150k**	**$667-958**
2,000	**3,000**	**2.5**	**8,100**	**$1,200-1,725k**	**$1,000-1,438**
1,000	**4,000**	**5**	**10,800**	**$1,600-2,300k**	**$2,000-2,875**

***Assumes total annual GHG emissions from SOVs of 13,500 MT CO_2e (see Table 1)**
****Assumes permit cost of $400-575/year**

Table 11: Costs of permits to ride-sharing drivers

# of passengers per vehicle	Daily fares collected*	Cumulative fares/yr.*	Net permit cost**
0	**0**		
0.25	**$0.50**	**$75**	**$425-644**
0.5	**$1.00**	**$150**	**$517-808**
1.5	**$6.00**	**$900**	**$100-538**
4	**$8.00**	**$1,200**	**$800-1,675**

*Assumes 150 round trip commutes per year, $2 per round trip.
**Cost = permit price in column 6 of Table 10 minus cumulative fares per year.

VI. Direct-to-Campus Rapid Transit (DCRT)

As noted earlier, the Santa Cruz Metro (SCMTD) carries about 2.5 million riders to and from UCSC every year. During peak demand hours, especially 7:30-9 AM, and 4-6 PM, bus capacity is strained to the breaking point; between peaks, buses may run almost empty. During peak hours, not only are the buses crowded, travel time can greatly exceed the nominal 10-15 minutes from Metro Center to campus, especially due to the high number of required stops. Moreover, at these times, buses often reach maximum load early in their trips, leaving passengers who live closer to campus stranded at bus stops as bus after bus passes them by. Moreover, those living outside the area directly served by UCSC-bound routes must transfer from one bus to another at the Metro Center, and can be affected by unreliable schedules and less frequent or missed runs, all of which also increase total travel time. The rational rider is provided a strong incentive to drive to campus.

Is there any way to address this time-of-day overload problem? One possibility is to increase the number of vehicles on routes during peak hours. That, however, requires more drivers and split shifts, all of which is costly. A second is to spread demand more evenly over the day via time-of-day (TOD) fares (as in London, for example). But students ride for “free” with their ID card; TOD fares would not affect them. A third is to develop dedicated direct bus runs (DCRT) to and from campus that would bypass the Metro Center and Westside stops. This might also be attractive to drivers, who would be able to avoid much of the inconvenience and crush during peak hours. There are, however, no recent data showing where faculty and staff live, which would be necessary to plan DCRT routes. Figures 5 and 6 show the spatial distribution of students and faculty in 1999. Since then, the student population has more than doubled, and high real estate prices have pushed students, faculty and staff farther from the campus. The two survey maps show that the highest concentration of students was within about two miles of campus; of faculty even less. We assume that campus growth and faculty retirements have pushed student, staff and faculty concentrations away from campus, raising average residence distances and inciting more driving. So, how can drivers be motivated to shift to public transit?

Figure 5: Student residence survey, 1999

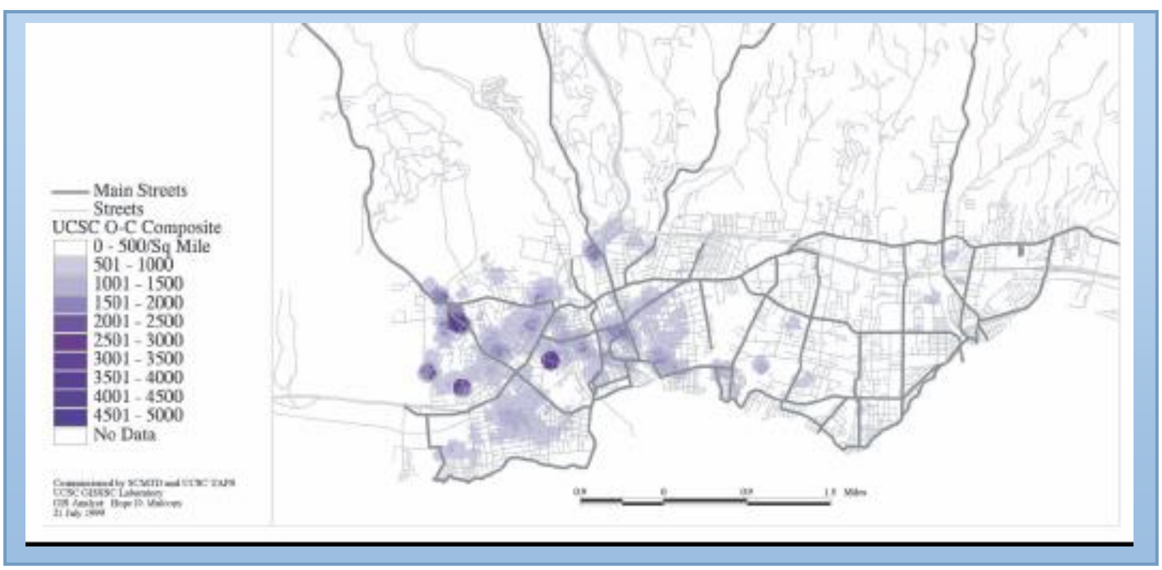
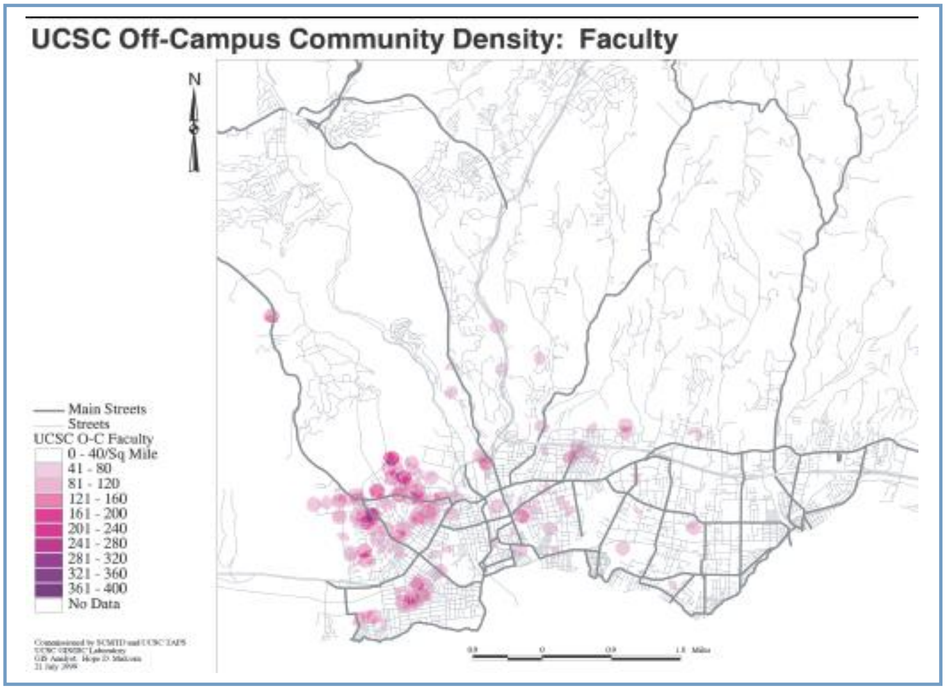


Figure 6: Faculty residence survey, 1999

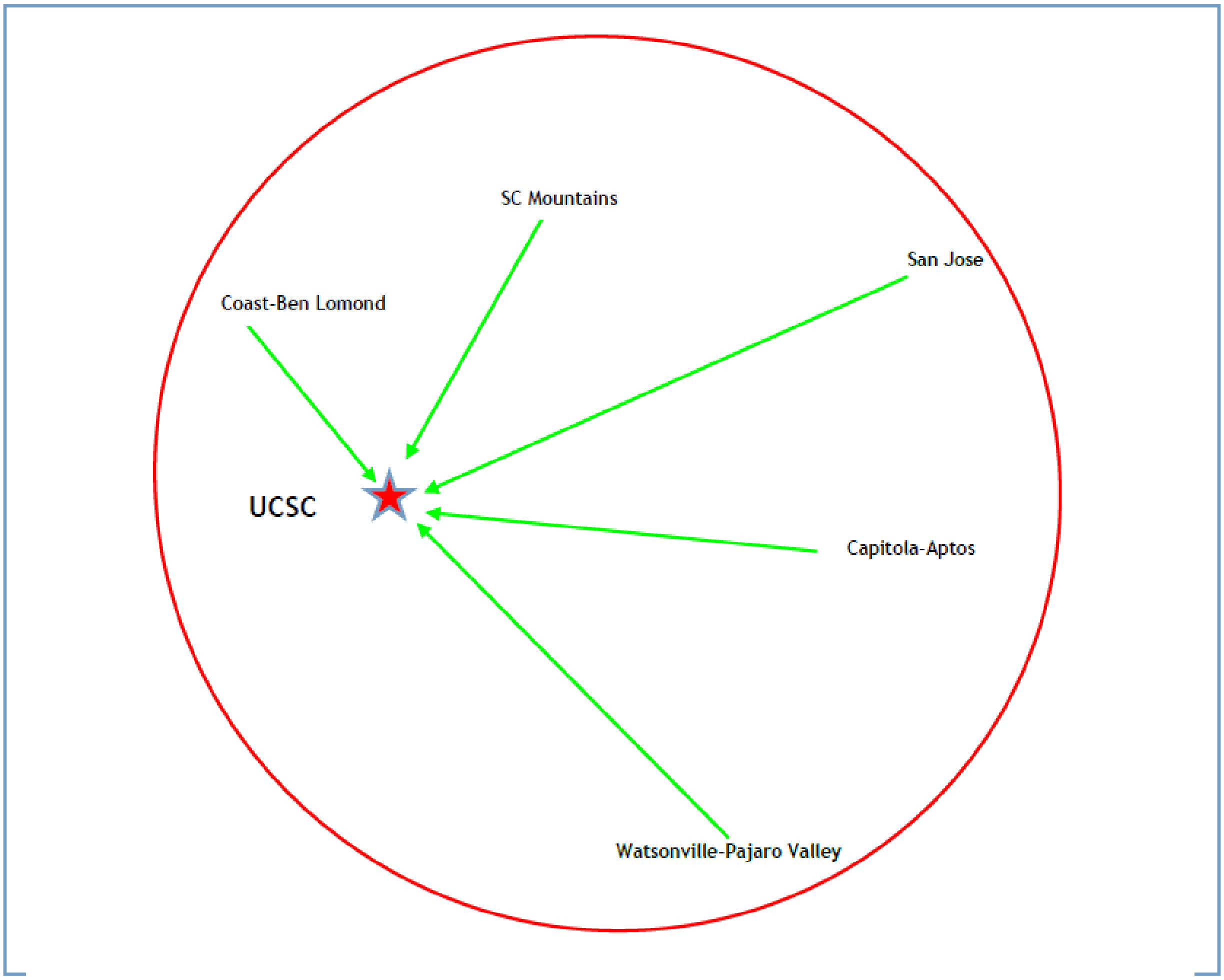


There are two aspects to this problem. The first is to make public transit easily accessible to riders and reduce travel time to and from campus so that is not much greater than driving. The second would be to schedule transit runs throughout the day, providing something closer to on-demand mobility to, from and across campus. DCRT (aka, "bus rapid transit" or BRT),[17] running on fixed-schedule, express routes from points of origin to campus with a few intermediate stops, could significantly decrease travel time from outlying areas (defined as any location requiring a change of vehicles, i.e. riding more than one Metro bus to campus). One example of DCRT-type arrangements are the private commuting buses operated by Silicon Valley firms to their campuses (although this creates split-shift problems for drivers). DCRT would operate along similar lines, although on a much smaller and less luxurious scale, with direct express buses to and from the campus at peak times, and smaller "jitney" vans (vanpool vans) during off-peak hours. Buses could be parked overnight at or near their starting points; drivers would either take their bus home and take the first morning run on the following day, or could leave their cars near the bus parking place and retrieve them after the return run in the evening. Vanpool vans could carry riders home throughout the day (or drop them off at intermediate stops[18] Figure 7 is an illustration of the UCSC ridershed and possible express bus routes.

[17] Robert Cervero, "Bus Rapid Transit (BRT): An Efficient and Competitive Mode of Public Transport," University of California Berkeley, Institute of Urban & Regional Development, Oct. 2013, at: http://escholarship.org/uc/item/4sn2f5wc (accessed 7/1/14).

[18] The Metro would have to be compensated for any loss of ridership on existing lines, although such compensation should be small, inasmuch as the express system is directed at those who do not commute to campus via the Metro.

Figure 7: Sample starting points and routes for express buses and jitneys



In Table 12, we estimate potential DCRT ridership and relative costs of four travel modes. We begin with a rider pool of 1,000 individuals (in reality, this number would be higher; 1,000 has been chosen for purposes of comparison). We have estimated the aggregated mileage for each mode, the total annual cost for each mode, and the cost per ride for each mode. Clearly, bus travel is the least costly mode, with carpools and vanpools coming in about three times as costly as buses. In Table 13, we have estimated the change in carbon dioxide emissions if it were possible to reduce by half the number of SOVs entering and leaving the campus (these numbers must be regarded as very rough estimates). What is clear is that the major reduction in SOV emissions is partially offset by the increase in carpool, vanpool and bus GHG emissions. This plan, too, would have the effect of reducing parking permit sales and could impose increased costs on TAPS for vanpool and bus operation (assuming vanpool and bus riders do not pay the full cost of rides), although riders would, presumably, considerably reduce their commuting costs and time, even while paying a nominal fare.

Table 12: Reductions in vehicles with ridesharing modes

Travel mode	Riders per vehicle	Total # of vehicles required	Aggregated mileage/yr*	Cost per mile**	Annual operating cost	Annual cost per rider	Notional capital cost†
SOV	1	1,000	6,000,000	$0.50	$3,000,000	$3,000	NA
Carpool	3	333	2,000,000	$0.60	$1,200,000	$1,200	NA
Vanpool	8	125	750,000	$1.50	$1,125,000	$1,125	2,500,000
Express bus	35	29	174,000	$2.00	$348,000	$348	7,250,000

*Assumes round trip of 30 miles/day; 200 days/yr.
** These are rough estimates taken from various sources. For a detailed discussion, see Victoria Transport Policy Institute, *Transportation Cost and Benefit Analysis II – Vehicle Costs* **,** Victoria, British Columbia, Sept. 13, 2013, Tables 5.1.12-1 & 12.2, at: http://www.vtpi.org/tca/tca0501.pdf (accessed June 30, 2015).
† Assumes $25,000 per van, $250,000 per bus.

Table 13: Comparative GHG emissions reductions from transportation modes

Mode	# of vehicles	total miles/yr.	kg. CO_2 emissions/mile	estimated total CO_2 emissions (MT)	current total emissions
SOV	2,400	14,400,000	0.44	6,336	13,531
Carpool	800	4,800,000	0.44	2,112	1,056*
Vanpool	300	1,800,000	0.66	1,188	184
Buses	70	417,600	0.97	5,275	4,871
				14,911	19,642

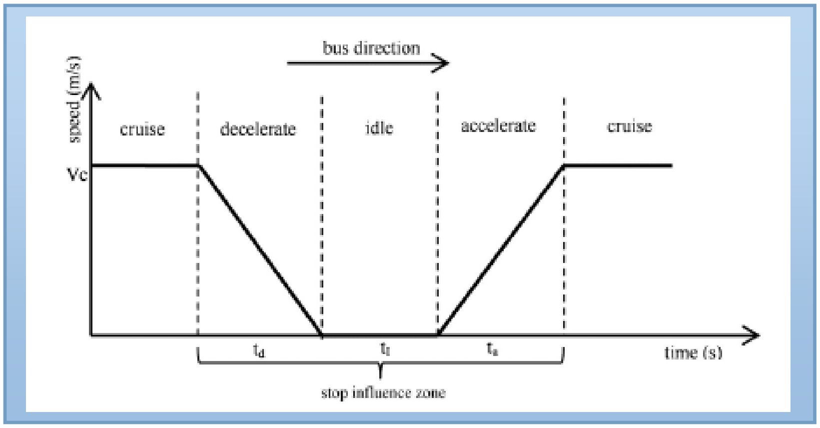
Source: Pageler GHG study
* Assumes 400 carpool trips per day

VII. Express bus runs on campus

We now turn from consideration of strategies to modify traffic entering and exiting the campus to potential modifications of on-campus transit. As noted earlier, during peak demand hours, a considerable fraction of passengers board and exit campus transit buses at five primary stops—East Remote, Baytree, Colleges 9 & 10, Science Hill and Porter/College Eight. Express buses running from the Main Entrance to the Baytree, College 9 & 10, and Science Hill would redistribute passenger loads and reduce stops, travel times and GHG emissions. How large might these reductions be? A major source of bus fuel consumption arises from slowing down, idling at bus stops and resuming speed.[19] This pattern is illustrated in Figure 8: in the "stop influence zone," fuel efficiency drops and emissions rise, and idling time is proportional to the number of passengers waiting to board the bus.

[19] Qian Yu & Tiezhu Li, "Evaluation of bus emissions generated near bus stops," *Atmospheric Environment* 83 (2014); Ricardo plc, "Research shows that smoothing traffic flow could significantly reduce bus emissions," Press release, July 21, 2014, at: http://www.ricardo.com/en-GB/News--Media/Press-releases/News-releases1/2014/Research-shows-that-smoothing-traffic-flow-could-significantly-reduce-bus-emissions/ (accessed 8/6/14).

Figure 8: Velocity pattern of a transit bus stopping for passengers



Source: Qian Yu & Tiezhu Li, "Evaluation of bus emissions generated near bus stops," *Atmospheric Environment* 83 (2014): 198.

To estimate potential time savings and GHG reductions from running express buses on campus, we draw on a recently-published modeling study of time and energy savings and carbon dioxide emission reductions as a result of elimination of bus stops in Fairfax, Virginia.[20] By calculating the time effects of acceleration and deceleration, and the dwell delay at each bus stop, the study found that a transit bus typically takes 20 seconds to slow down, pick up riders, and accelerate back to cruising speed (this is a very short time in the stop influence zone, as UCSC bus riders well know). The high number of bus stops on the original Fairfax route was cut by almost 50%, reducing travel time in the model by 23%. The study's authors assumed an hourly bus operating cost of $51.76, suggesting that reduced travel time could save as much as $12 per hour. Finally, the study found that CO emissions could be reduced by 34% (CO_2 emission reductions were not calculated, but would be in a similar range).[21] A second empirical study of bus travel times during peak and off-peak hours in Nanjing, China found a reduction of about 46% in CO_2 emissions between the two periods as a result of difference in stop influence zone times.[22] A third empirical study in Beijing calculated that a reduction in average speed from 25 to 15 km/hr. led to an increase in emissions of approximately 20-30% for diesel buses, 30-45% for natural gas powered buses, and 50% for hybrid diesel buses.[23]

[20] Ranjay M. Shrestha & Edmund J. Zolnick, "Eliminating Bus Stops: Evaluating Changes in Operations, Emissions and Coverage," *Journal of Public Transportation* 16, #2 (2013): 153-75.
[21] Shresta & Zolnick, "Eliminating Bus Stops," p. 166-67.
[22] Qian Yu & Tiezhu Li, "Evaluation of bus emissions generated near bus stops," *Atmospheric Environment* 85 (2014): 195-203, p. 200.
[23] Shaojun Zhang, et al., "Real-world fuel consumption and CO_2 emissions of urban public buses in Beijing," *Applied Energy* 113 (2014): 1645-55, pp. 1648-49.

To calculate emission reductions due to express buses on campus, we make the following assumptions for UCSC vehicles:[24]

- Fuel economy (miles/gallon; km/liter): 10 mpg; 4 km/l
- Average velocity (km./hr.): 15-25 mph; 24-40 km/hr
- Time delay per bus stop: 60 sec
- Stopping zone: 100 meters
- CO_2 emissions during normal operation (kg/km): 1,000 g/km
- CO_2 emissions during slowing, stopping, starting (kg/km): 3,000 g/km

We compare the difference in travel times and emissions for a local loop bus and an express bus, both running from the Main Entrance to Science Hill. Including starting and ending points, a loop bus makes eight stops, while an express bus makes none (we ignore stop signs, since both local and express buses must stop at them). Assuming that the distance from the Main Entrance to Science Hill is 3 miles, or 5 kilometers, trip time for an express bus traveling at 25 miles/hour is approximately 7 minutes, leading to CO_2 emissions of roughly 6.6 pounds (3 kilograms). For a local bus with a cruising speed of 10 miles/hour and making all eight stops, travel time including an idling time of one minute per stop will be 14 minutes, with emissions of 19.8 pounds (9 kg), or three times as much.

Earlier in this study, we offered an estimate of 200 loop runs per day (assume upper campus runs will remain local). Total CO_2 emissions from loop runs (5 miles or 8 km.) will be approximately 10,560 pounds (4.8 MT CO_2e kg) per day. If 20% of those runs are express buses on a 6 mile trip (3 miles each way, or 10 km.), the reduction in emissions from the base case will be approximately 1,760 pounds (800 kg), or 17%. Note that, in the absence of riders taking the return trip, express buses must run empty to their starting points or the garage. These numbers are very rough estimates, but suggest that the savings from express buses would come primarily in travel time and some reduction in congestion. The change in overall transportation emissions is rather small. We have not tried to calculate the economic value of reduced travel time and congestion.

VIII. Demand-response transit

Demand-response systems operate much like the ridesharing programs described above: Riders send pickup requests to a computerized dispatching center, via smartphones or some other type of communication. The computer identifies the best route and the closest available vehicle, dispatches the vehicle to the pickup point(s), which delivers riders to their desired destination(s). Ideally, demand-response responds to need and operates with vehicles near or at full capacity. This means that fewer buses run partially or completely empty and, depending

[24] Data from Yu & Li, "Evaluation" op cit.; TAPS, "UCSC Fleet Fuel Use"; Aijuan Wang, et al., "On-road pollutant emission and fuel consumption characteristics of buses in Beijing," *Journal of Environmental Sciences* 23, #3 (2011): 419–426.

on the drive system in the smaller vehicles, reduces aggregate GHG emissions. Because rider demand varies over time and space, a demand-response transit fleet needs to include vehicles of varying size and capacity: if 25 riders are waiting at a bus stop, a full-sized bus is dispatched; if only six are waiting, a van is sent. When the trip is completed, the vehicle can be sent to the nearest site of demand, reducing down time and deadheading back to the waiting site, or it can wait at the drop-off point until new demands are sent in. Either way, this reduces unnecessary travel and vehicle crowding.

Most existing demand-response systems in the United States are designed for mobility-impaired and developmentally-disabled riders, who are unable to drive or access fixed transit routes. Many of the systems that call themselves "demand-response" require reservations up to 24 hours in advance, although there are some, such as the Clinton County, Michigan "Blue Bus" system[25] and *Kutsuplus* in Helsinki,[26] that allow riders to schedule pickups with less advance notice. Most demand-response systems also offer pickup at and return to a rider's residence and do not stop at fixed pickup points or prescribed routes. This can add to both ride time and distance, as well as stops and starts, especially if the vehicle is transporting multiple passengers to different destinations.

A UCSC campus demand-response system would be designed to operate in real time, without advance reservations, and to utilize the existing somewhat differently from these. Currently, throughout the day, TAPS runs full-sized buses on campus routes, regardless of rider demand at the stops around campus. A demand-response dispatch system would run full-size buses and smaller vehicles depending on the TOD demand and rider destinations. Because there is a limited number of pickup and destination points on campus (in addition to bus stops), the system could be programmed with fixed routes in addition to Loop and Upper Campus (e.g., a van picking up at Earth & Marine Sciences and delivering riders to Stevenson). A pure demand-response system could require additional drivers and increase GHG emissions. A hybrid-system—fixed routes at peak times (with express runs) and demand-response at other times—would reduce emissions from buses and add emissions from vans. If it were possible to press hybrid or EV vanpool vans into service between 9 AM and 4 PM, with drivers transferring from large buses to vans, we might see emissions reductions. Here, we can offer only a very rough model of a demand-response system; a more precise model would require fairly sophisticated programming as well as TOD pickup and destination data, both of which are beyond the scope of this study.[27]

We assume that full-size buses, however powered continue to operate during peak hours. We also assume that, between peak hours, as shown in Table 6 above, rider demand

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[25] "About Clinton Transit," at: http://www.clintontransit.com/about-us/ (accessed 8/25/14).

[26] Keith Barry, "New Helsinki Bus Line Lets You Choose Your Own Route," *Wired*, Oct. 11, 2013, at: http://www.wired.com/2013/10/on-demand-public-transit/ (accessed 8/25/14).

[27] A number of companies offer demand-response software; see, e.g., Trapeze, "Demand Response Transportation Management Software," at: http://www.trapezegroup.com/novus# (accessed 8/25/14) and RouteMatch Software, "Demand Response and Paratransit," at: http://routematch.com/solutions/demand-response-and-paratransit/ (accessed 8/25/14).

across campus is about 300 rides per hour, or 50 riders per each 10 minute period. These riders are distributed among five bus stops, which implies five riders per stop in each direction. We further assume that these five riders each have different destinations, although they are all in the same direction of travel (east or west). A 6-8 person van, dispatched to pick up three riders at a specific stop could deliver them to their desired stop within 10 minutes of demand (5 minutes to arrive, 5 minutes to deliver). Vans could also make intermediate stops, as necessary. For the purposes of this study, we assume that 10 commuter vans are in continuous operation during a typical, non-peak hour. These replace the six Loop and eight Upper Campus bus runs during the same period of time. Table 14 compares the GHG emissions of different transit configurations. The GHG reductions from this hybrid demand-response configuration are about 20-30%, although the precise number depends on configuration and the number and type of vehicles deployed. Reduced travel time across campus could represent a significant benefit, especially for faculty and staff, many of whom now drive their cars to and across campus. At the same time, however, the overall cost is likely to be quite high, and it is not clear that the benefits can offset potentially higher labor and maintenance costs.

Table 14: GHG emissions from current & demand response configurations during one off-peak hour

Transit configuration	Miles covered per hr.	CO_2 emissions in g/mile*	Total (kg)
Current			
6 Loop runs/hour	30 miles	EV: 0 Hybrid: 2300 Diesel or CNG: 3000	0 69 90
8 Upper campus runs/hr.	24 miles	EV: 0 Hybrid: 2300 Diesel or CNG: 3000	0 55 72
Total current	54 miles		EV: 0 Hybrid: 124 Diesel or CNG: 162
Demand response			
10 vans for 1 hour	200 mi (@ 20 mph avg.)	EV: 0 Hybrid: 440 Gasoline: 660	0 88 132

*EVs emit nothing at the tailpipe, but total operating emissions depend on the power source.

IX. Hybrid electric vehicles

Could we make the campus bus fleet partially or wholly electric and recharge them with only renewable energy sources? In this section, we discuss hybrid electric vehicles (HEVs); in the next, electric-only vehicles (EVs). A growing number of metropolitan transit systems are incorporating HEV buses into their fleets,[28] and the operating record of such vehicles is well-documented. At the same time, a few transit systems have found that the benefits of HEV

[28] See the Wikipedia page http://en.wikipedia.org/wiki/Hybrid_electric_bus#Conversions

buses do not offset costs associated with them (remember that nonmonetary benefits cannot offset real money costs). While the immediate impact of hybridization and/or electrification on UCSC GHG emissions would be relatively small, the symbolic significance cannot be overestimated.

Two different hybrid configurations are available. The most important distinction between them involves the design of the HEV drive train, having to do with whether the internal combustion engine is connected directly to the axles or whether the engine generates power to run the electric motors that turn the axles (see Figure 9). *Parallel drive* systems are found in most hybrid cars, which operate on electric motors at low velocities and gasoline or diesel at highway speeds. Batteries are charged through regenerative braking—in effect, a generator that works with the brakes to slow the car down—and, as necessary, by the internal combustion engine running a generator. *Series drive* systems use a small, (usually) fossil fueled engine to generate the power transmitted to the axles, with a battery for electricity-only operation. These systems work best for low speed, in-city driving, especially where there are steep hills, because they provide rapid acceleration and power surges for climbing inclines (the San Francisco Metropolitan Transit Authority, aka "Muni," runs series hybrids). A series drive bus would seem most appropriate for UCSC, given its hilly configuration.[29]

Figure 9: Bus drive train configurations

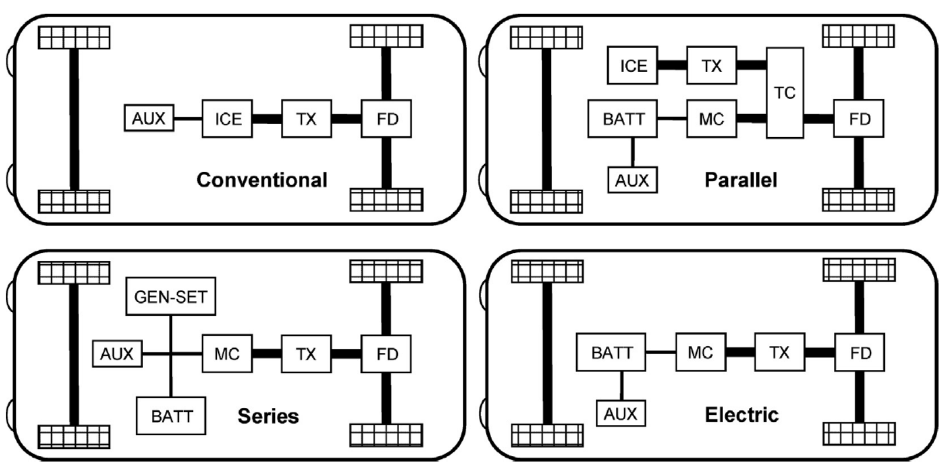

Fig. 1. Simplified layouts of the different city bus configurations (ICE = diesel engine, TX = transmission, FD = final drive, AUX = auxiliary devices, TC = torque coupler, MC = motor/controller, BATT = battery, GEN-SET = engine-generator).

Source: Antti Lajunen, "Energy consumption and cost-benefit analysis of hybrid and electric city buses," *Transportation Research Part C* 38(2014)1–15, p. 3.

Table 15 lays out the alternatives in terms of replacing diesel- and gasoline-fueled buses. These numbers are subject to considerable variation, and should be regarded as approximations for comparative purposes. What is clear is that the tradeoffs between,

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[29] Buses that draw electricity from fuel cells are in the design and testing stage. This addresses the energy storage problem, but these are not considered here.

compressed natural gas (CNG) and HEV buses, in particular, are fairly minimal, because series hybrids generate electricity primarily via combustion.

Table 15: Comparative statistics for different bus drive train configurations

Technology	**Fuel efficiency** (mpg equiv.)	**CO_2 emissions** (g/mi.)	**Capital cost**	**Life cycle Cost/mile**
Hybrid electric	3-5.6	2100-2500	$550,000	$2.04-3.04
Electric	1.9-2.5 kWh/mi or 17 mpge	0 (at bus--depends on generating fuel)	$550,000- $1,000,000	$1.61-2.68
Fuel cell	6-8 mpge	0 (at bus)	$1,500,000	No data
Diesel	2.3-4.2	2700-3400	$370,000	$1.55
CNG	2-6	2700-3500	$450,000	$1.62-2.58

Sources: R. Ahluwalia, X. Wang & R. Kumar, "Fuel Cell Transit Buses," A *Argonne National Laboratory, Argonne, IL* (Jan 31., 2012), at: http://www.ieafuelcells.aeat.com/documents/Fuel_Cells_for_Buses_Jan_2012.pdf (accessed 8/18/14); Shauna L. Hallmark, et al., "Evaluation of In-Use Fuel Economy for Hybrid and Regular Transit Buses," *Journal of Transportation Technologies* 3 (2013): 52-57; Antti Lajunen, "Energy consumption and cost-benefit analysis of hybrid and electric city buses," *Transportation Research Part C* 38(2014)1–15; Steve Richardson, "Hybrid-Diesel vs. CNG--An updated comparison of transit fleet alternatives," Public Solutions Group, Ltd, Jan. 2013, at: http://publicsolutionsgroup.publishpath.com/Websites/publicsolutionsgroup/files/Content/1417809/Transit_Hybrid-Diesel_vs._CNG.pdf; Zlatomir Živanović and Zoran Nikolić, "The Application of Electric Drive Technologies in City Buses," ch. 6, in: Zoran Stevic (ed.), *New Generation of Electric Vehicles,* Dec. 12, 2012, at: http://www.intechopen.com/books/new-generation-of-electric-vehicles/the-application-of-electric-drive-technologies-in-city-buses (accessed 8/12/14); Shaojun Zhang, et al., "Real-world fuel consumption and CO_2 emissions of urban public buses in Beijing," *Applied Energy* 113 (2014): 1645-55; Aijuan Wang, et al. "On-road pollutant emission and fuel consumption characteristics of buses in Beijing," *Journal of Environmental Sciences* 23, #3 (2011): 419–426; Ward Thomas, "Electric Buses at Stanford," Parking & Transportation Services, Stanford University, at: http://chesc.org/documents/ThomasWard_Jun173113Adams4.15pm_000.pdf (accessed 8/18/14).
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A parallel, plug-in hybrid emits less carbon dioxide than CNG *at the tailpipe* because, at low velocities, the HEV runs primarily on electricity. As noted above, however, parallel hybrids may have trouble on steep inclines such as are found on the UCSC campus. It is not evident, either, that replacing the current bus fleet with HEV buses would represent a significant net reduction in GHG emissions, when compared to CNG fuelled vehicles. The cost of a new HEV fleet would almost certainly be more than CNG-fuelled buses, even after paying an emissions penalty.

One potential way to reduce the capital costs of HEVs is to replace fossil-fueled *drive trains* in buses purchased when the current bus fleet is replaced. Companies such as Wrightspeed[30] are building hybrid electric drive trains to replace original internal combustion and diesel ones. To date, these are available only in heavy-duty trucks (whose cost is proprietary information), light cargo vans and small shuttle buses (for an estimated $8,000 per

[30] Jeff Cobb, "Wrightspeed Combines Gas Turbine and Batteries for Big Fuel Savings," Hybridcars.com, Feb. 18, 2014, at: http://www.hybridcars.com/wrightspeed-combines-gas-turbine-and-batteries-for-big-fuel-savings/ (accessed 8/12/14). See http://wrightspeed.com/products/the-route/ for system specifications and design.

conversion).[31] Over the next few years, assuming sufficient demand, replacement drop-in electric hybrid drive trains are likely to become available for buses, which will offer a less-costly alternative to hybrids than buying new or used HEVs.

X. All-electric vehicles

Wholly-electric, "plug-in" buses are available but, as is the case with EVs in general, they are distance limited,[32] require high-capacity, expensive batteries, and can require a long time to charge (although "fast-charge" systems are in testing that can recharge a bus battery in as little as 15 seconds).[33] For EVs, GHG emissions are associated with the electricity-generating source rather than vehicle operation and, depending on the power source, these may be difficult to calculate. Technically speaking, such emissions are calculated on the basis of the power-providing producer's fuel mix. Hence, a consumer who contracts with a producer or seller generating electricity wholly from hydro can claim zero emissions at the source. But this claim is a bit misleading, because electrons and electricity generated from fossil fuels are indistinguishable from those coming from renewable sources.

A more accurate approach is to look at the total mix of power generation within the Western U.S., much of which comes from coal and natural gas (Figures 10 & 11).[34] Aside from periodic cogenerated power and a small quantity of solar electricity from campus facilities, UCSC's electricity is currently supplied by Pacific Gas & Electric, which estimates a 2014 GHG emission factor of 0.187 MT CO_2 per megawatt-hour.[35] Stanford University's "Marguerite" transit system runs a number of HEV and EV buses; Figures 11 and 12 provide some operating and cost data for that bus fleet.

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[31] Daniel Gross, "In for the long haul," *Slate*, May 14, 2014, at: http://www.slate.com/articles/business/the_juice/2014/05/hybrid_vehicles_xl_hybrids_has_found_a_big_new_audience_for_them.html (accessed 8/24/14); BusinessWire, "XL Hybrids Expands Its Hybrid Electric Powertrain Technology to Ford E-Series Cutaway and Strip Chassis," March 5, 2014, at: http://www.businesswire.com/news/home/20140305005045/en/XL-Hybrids-Expands-Hybrid-Electric-Powertrain-Technology#.U_pJqmPAbxw (accessed 8/24/14).

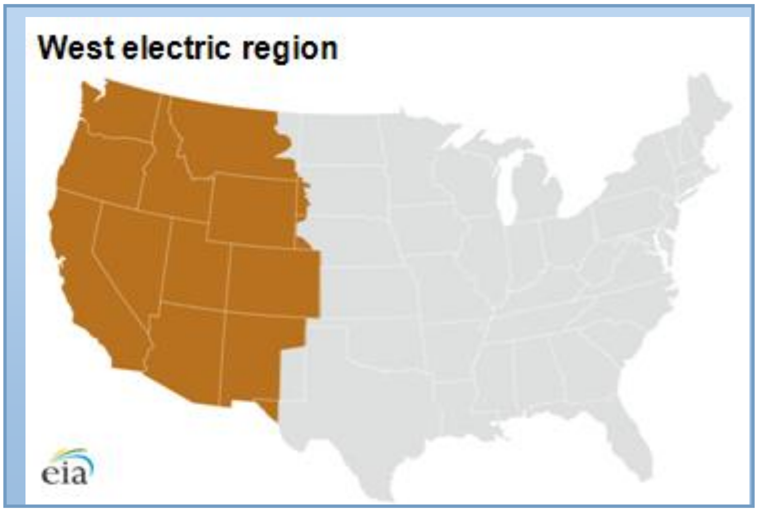
[32] According to Ward Thomas ("Electric Buses at Stanford"), Stanford's test of EV buses can go as far as 125 miles between charges (equal to 25 loops at UCSC).

[33] Amanda Kooser, "Battery-topped electric buses flash charge in 15 seconds," *C/net*, June 16, 2014, at: http://www.cnet.com/news/battery-topped-electric-buses-flash-charge-in-15-seconds/ (accessed 8/24/14).

[34] U.S. Energy Information Administration, "Existing Resource Base and Policy Decisions provide the West with electric fuel diversity," *Today in Energy*, Dec. 11, 2013, at: http://www.eia.gov/todayinenergy/detail.cfm?id=14131 (accessed 8/24/14).

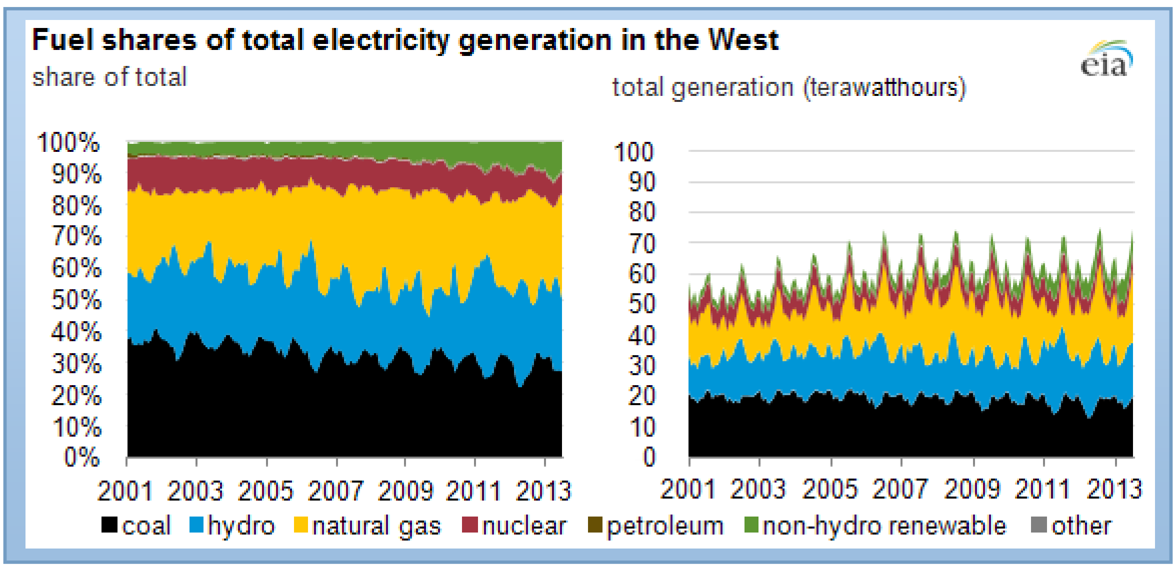
[35] Pacific Gas & Electric, "Greenhouse Gas Emission Factors: Guidance for PG&E Customers," April 2013, at: http://www.pge.com/includes/docs/pdfs/shared/environment/calculator/pge_ghg_emission_factor_info_sheet.pdf (accessed 8/24/14).

Figure 10: Western Electricity Coordinating Council region (excluding Canada)



Source: U.S. Energy Information Administration, "Existing resource base and policy decisions provide the West with electric fuel diversity, Dec. 11, 2013, at: http://www.eia.gov/todayinenergy/detail.cfm?id=14131# (accessed Nov. 7, 2014)

Figure 11: Fuel shares of total electricity generation in the Western United States



Source: U.S. Energy Information Administration, "Existing resource base and policy decisions provide the West with electric fuel diversity, Dec. 11, 2013, at: http://www.eia.gov/todayinenergy/detail.cfm?id=14131# (accessed Nov. 7, 2014)

Figure 12: Stanford's bus fleet

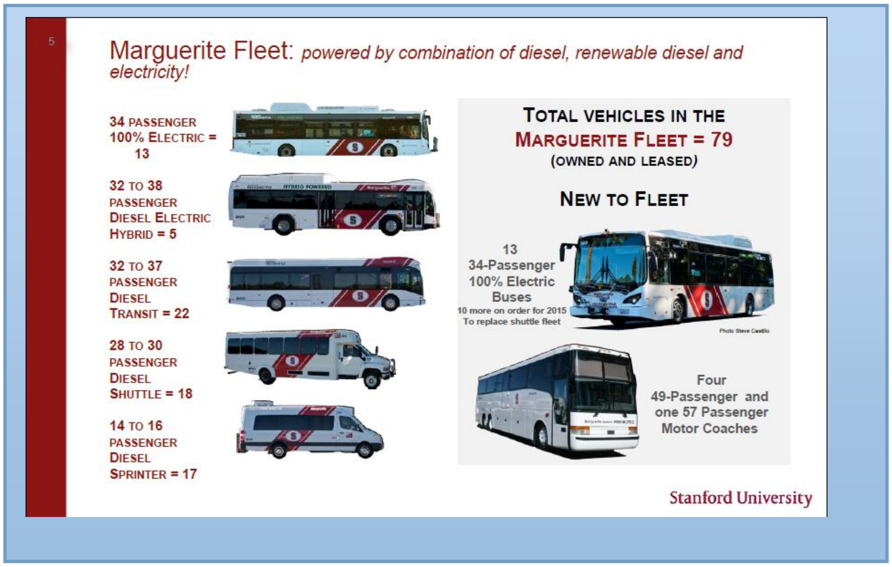
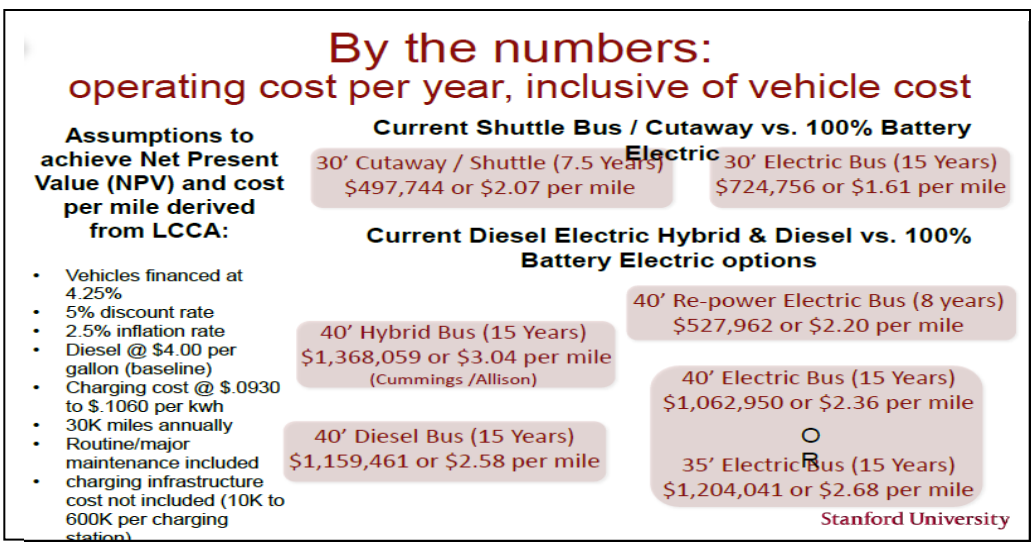


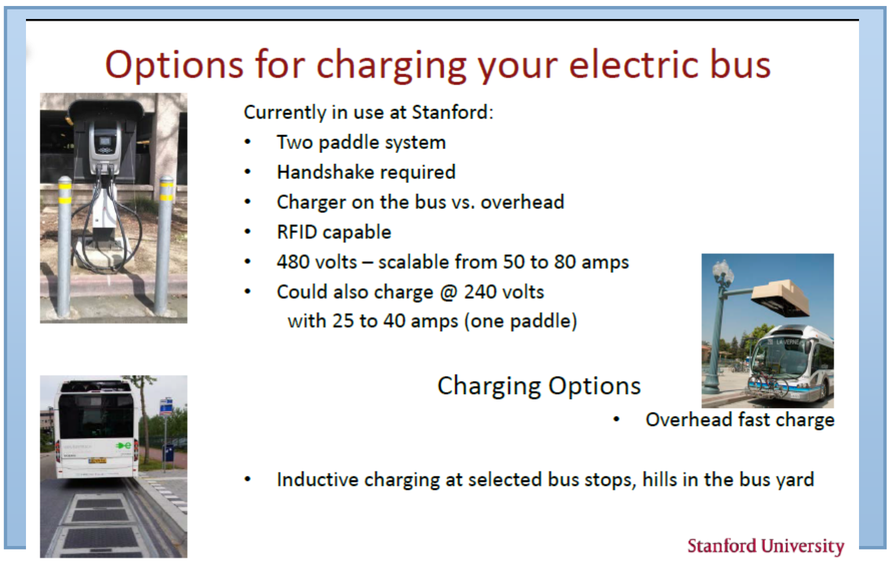
Figure 13: Comparative bus costs at Stanford



Source for both figures: Ward Thomas, "Electric Buses at Stanford," Parking & Transportation Services, Stanford University, at: http://chesc.org/documents/ThomasWard_Jun173113Adams4.15pm_000.pdf (accessed 8/18/14).

Were electricity to come from photovoltaics (PVs) installed on campus—wind energy does not appear feasible at UCSC due to local wind conditions over the year—there would be no immediate greenhouse gas emissions from either electricity generation or vehicle operation (for the present purposes, we ignore life cycle GHG emissions from PVs and different bus drive systems and consider only operating emissions. Generally speaking, transit EVs would need to operate on a single charge during the day and recharge at night. Of course, peak solar PV generation comes in the middle of the day, when vehicles are in operation.[36] That would make it necessary to have large banks of storage batteries for daytime charging or some kind of quick charge system (see Figure 14; note that these are not PV powered charging options). One potential solution to this dilemma is use of vanpool EVs vans for daytime power storage; the vans could then provide quick recharges to buses. But the vans are used for commutes and, potentially, for a demand-response system and would require their stored power for operation.

Figure 14: EV charging options



Source: Ward Thomas, "Electric Buses at Stanford," Parking & Transportation Services, Stanford University, at: http://chesc.org/documents/ThomasWard_Jun173113Adams4.15pm_000.pdf (accessed 8/18/14).

To compare the costs and GHG emissions of different EV configurations, we make the following assumptions:

- 38-passenger electric bus travelling 20 loops per day (100 miles/day);
- fleet of 20 buses travelling 2,000 miles/day;
- energy consumption of 2.25 kWh/mile (based on Stanford data);
- average PV generation from 1 kW array in Santa Cruz is 5 kWh;
- no DC to AC conversion required for charging batteries;
- PV cost of $3,000/kW installed;
- 15 year system lifetime;

[36] Under an agreement with PG&E, University of California campuses are not permitted to send PV surpluses into the utility grid (although this agreement is being renegotiated). This means that either systems are too small to provide more than a fraction of campus demand, or that surplus electricity must be dumped to ground.

- cost of storage batteries $500/kWh;
- academic year of 175 days; generation year of 365 days;
- average daytime cost of PG&E electricity of $0.11/kWh, nighttime cost of $0.08/kWh (E20 tariff; Table 15)[37];
- interest rates of 4% & 7%/yr.

The estimates shown below are necessarily crude, since we make no assumptions about financing arrangements, subsidies or other incentives that could lower system and generation costs.

- Buses require 4,500 kWh/day of electricity (2,000 mi/d x 2.5 kWh/mi.)
- Annual bus electricity requirement (175 days/yr.):790,000 kWh
- Power requirement: 900 kW (4,500 kWh/day ÷ 5 kWh/kW-day)
- System size: 1 MW, which generates 1,642,500 kWh over 365 days
- PV system cost: $3,000,000 (1 MW @ $3,000/kW)
- Storage battery cost: $2,250,000 ($500/kWh x 4,500 kWh)
- Loan cost @ 4% & 7% for 15 years: $9,450,000-$14,421,000
- Levelized cost of electricity w/ batteries: $0.38-0.59/kWh
- Grid electricity cost (15 yrs. @ $0.08/kWh: $948,000

These numbers do not include the capital cost of the vehicles or charging facilities, which will be the same whether buses draw on PV or the utility grid. What is clear is that, for the moment, the cost of power from the grid is far less than from a PV array. The storage batteries more than double the cost of electricity but, even without them, the PG&E rate would still be far less.

What about comparative GHG emissions? Again excluding life cycle emissions from the calculation, and focusing only on energy-related emissions, we see that the penalty from charging from the grid is relatively minor (Table 16). The excess cost of relying on PV power (the difference between the cost of PV and grid electricity, which is roughly $0.30/kWh) amounts to almost $240,000. In other words, while it would be symbolically important to rely on PVs to power an EV bus system, and might even make sense in the future if fuel and electricity costs rise substantially, for the time being this approach would be highly irrational

[37] **Table 16: PG&E time-of-day tariffs for customers with demand of 1000 kW or more**

Tariff name	Hours	Cost per kWh
Summer, 5/1-10/31		
Summer peak	M-F, 12 noon – 6 PM	$0.148
Summer partial peak	M-F, 8:30 AM – 12 noon & 6-9:30 PM	$0.104
Summer off-peak	M-F, 9:30 PM- 8:30 AM & all day weekends & holidays	$0.079
Winter, 11/1-4/30		
Winter partial-peak	M-F, 8:30 AM – 9:30 PM	$0.099
Winter off-peak	M-F, 9:30 PM – 8:30 AM & all day weekends & holidays	$0.083

We assume that maximum demand occurs from 9/20-6/15, skewing average cost toward winter peak. Pacific Gas & Electric, "Electric Schedule E-20," April 30, 2014, p. 3, 7 at: http://www.pge.com/tariffs/tm2/pdf/ELEC_SCHEDS_E-20.pdf (accessed 8/24/14).

from an economic perspective. If hybrid electric commuter vans could be used for daytime storage and recharging, the economics of reliance on PVs might change, but only at the cost of higher GHG emissions from the vans (it would make more sense to operate wholly-electric vans and charge them at night). In other words, if UCSC wants to move to EV buses, that will have to be justified on a different basis.

Table 17: Comparative GHG emissions from different EV bus configurations*

Configuration	**GHG emissions factor** (MT/MWh)	**GHG emissions per year** (MT)	**Cost of emissions @ $12 MT permit**
Photovoltaics	0	0	0
PG & E power	0.187	148	$1,776
West. Interconnect	0.44	348	$4,176

***We do not know what fraction of PG&E's power may come through the Western Interconnection. Presumably, its GHG emissions factor incorporates emissions from those sources.
Source**:** Pacific Gas & Electric**, "**Greenhouse Gas Emission Factors: Guidance for PG&E Customers, April 2013, at: http://www.pge.com/includes/docs/pdfs/shared/environment/calculator/pge_ghg_emission_factor_info_sheet.pdf (accessed 8/24/14); Joseph A. Cullen & Erin T. Mansur, "Will Carbon Prices Reduce Emissions in the UD Electricity Industry? Evidence from the Shale Gas Experience," March 31, 2014, p.8, at: http://www.dartmouth.edu/~mansur/papers/cullen_mansur_gasprices.pdf (accessed 8/25/14).

XI. Autonomous transit vehicles[38]

The final change we consider in this study is the introduction of autonomous vehicles (AVs) into the campus transit mix. This is not as far-fetched as it might seem, even though a considerable number of both technological and social complications remain to be addressed. Small-scale autonomous transit vehicles are already being deployed at sites around the world. These are low-capacity (van-sized, carrying on the order of six to ten riders) and run on relatively low-traffic sites,[39] but development of more sophisticated systems capable of operating on city

[38] A recent overview of autonomous vehicles is James M. Anderson, et al., *Autonomous Vehicle Technology—A Guide for Policymakers*," Santa Monica, Calif.: RAND Corporation, 2014, at: http://www.rand.org/content/dam/rand/pubs/research_reports/RR400/RR443-1/RAND_RR443-1.pdf (accessed 8/27/14). There are both optimistic and pessimistic views of the potential for driverless transit vehicles; see Nick Collings, "Driverless buses on the way," *The Telegraph*, Oct. 22, 2014, at: http://www.telegraph.co.uk/news/uknews/road-and-rail-transport/11180429/Driverless-buses-on-the-way.html (accessed June 30, 2015), and Eric Jaffe, "Don't Expect to Ride in Driverless Buses Anytime Soon," *Atlantic City Lab*, March 16, 2015, at: http://www.citylab.com/tech/2015/03/dont-expect-to-ride-in-driverless-buses-anytime-soon/387844/ (accessed June 30, 2015).

[39] "Trials for Singapore's first driverless vehicle." Phys.org., Aug. 16, 2013, at: http://phys.org/news/2013-08-trials-singapore-driverless-vehicle.html (accessed 11/7/13); see also Glenn McDonald, "London Tests Driverless Shuttle Buses," *Discovery News*, Feb. 19, 2015, at: http://news.discovery.com/autos/future-of-transportation/london-tests-driverless-shuttle-buses-150219.htm (accessed June 30, 2015). See also NAVYA, at: http://navya-technology.com/?lang=en (accessed June 30, 2015).

streets is judged to be only a matter of time.[40] AVs use GPS to follow routes and visual and radar systems to detect actual or potential obstacles to be avoided; they may also communicate with other vehicles as a way of maintaining "awareness" of and distance from nearby objects. Passenger-size AVs are currently permitted on California streets and highways,[41] and are being extensively tested. Many popular articles report AVs to be safer than driver-operated vehicles,[42] although Google's recent report on the safety records of its AVs suggest they may be prone to being rear-ended at traffic lights.[43]

A key safety and liability consideration involves "UMOs": unidentified (or unseen) moving objects.[44] AV programming assumes a reasonably-stable operating environment—cars, streets, lights, curbs, etc.—whose presence, character and stability can be incorporated into the operating software. As any driver knows, however, streets and roads are full of unpredictable events and wayward objects, to which drivers must respond almost instantaneously, if not to suffer a collision or accident. On city streets, in particular, pedestrians and bicycles with low radar profiles and no locational transponder can appear out of nowhere (of course, if everyone were to carry a beacon-equipped device such as a smartphone, they would be "visible" to both AVs and the authorities). On the UCSC campus, in addition to the always-unpredictable and inattentive students looking at their phones or feet, there are also deer—which never carry smartphones (unless they are all tagged with RFID chips). UC is "self-insuring"—that is, the campuses are directly responsible for any liability resulting from on-campus or university-associated activities. As a result, UC administrators are extremely risk averse. Until liability issues are resolved—who is the responsible agent when an AV is involved in an accident or encounter with a pedestrian or bicycle?—there are likely to be significant restrictions on campus deployment.[45]

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[40] Carlos Fernandez, et al., "Autonomous Navigation and Obstacle Avoidance of a Micro-bus," *International Advanced Robotic* Systems 10, #212 (2013), at: http://www.mrt.kit.edu/z/publ/download/InTech-Autonomous_navigation_and_obstacle_avoidance_of_a_micro_bus.pdf (accessed 8/27/14); Mark Piesing, "Autonomous vehicles: How safe are trucks without human drivers," The *Independent*, Jan. 9, 2014, at: http://www.independent.co.uk/life-style/gadgets-and-tech/features/autonomous-vehicles-how-safe-are-trucks-without-human-drivers-9047546.html (accessed 8/27/14).

[41] SB-1298 Vehicles: autonomous vehicles: safety and performance requirements, at: http://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=201120120SB1298 (accessed Nov. 7, 2014).

[42] Tom Simonite, "Data Shows [sic] Google's Robot Cars are Smoother, Safer Drivers than you or I," *Technology Review*, Oct. 25, 2013, at: http://www.technologyreview.com/news/520746/data-shows-googles-robot-cars-are-smoother-safer-drivers-than-you-or-i/#comments (accessed Nov. 7, 2014); Mark Piesing, "Autonomous Vehicles: How safe are trucks without human drivers?" *The Independent*, Jan. 9, 2014, at: http://www.independent.co.uk/life-style/gadgets-and-tech/features/autonomous-vehicles-how-safe-are-trucks-without-human-drivers-9047546.html# (accessed Nov. 7, 2014).

[43] "Google Self-Driving Car Project Monthly Report," May 2015, at: http://static.googleusercontent.com/media/www.google.com/en/us/selfdrivingcar/files/reports/report-0515.pdf (accessed June 30, 2015).

[44] C. E. Smith, C. A. Richards, S. A. Brandt, and N. P. Papanikolopoulos, "Visual tracking for intelligent vehicle-highway systems," *IEEE Trans. Veh. Technol.*, vol. 45, pp. 744–759, Nov. 1996.

[45] Gary E. Marchant & Rachel A. Lindor, "The Coming Collision between Autonomous Vehicles and the Liability System," *Santa Clara Law* Review 52, #4 (Dec. 17, 2012): 1321-40, at: http://digitalcommons.law.scu.edu/lawreview/vol52/iss4/6 (accessed 8/27/14). Some argue that this is not an issue. Because an accident is assumed to be problem of product malfunctioning, manufacturers can be sued for

Autonomous vehicle transit schemes tend to hew to two basic architectures. One assumes vehicles, as above, that are programmed on fixed routes marked by waypoints (Figure 15a); a second is based on demand-response programming, relying on GPS to pick up and drop off riders (Figure 15b). A UCSC system would probably draw on both elements, with Loop and Upper Campus vehicles operating on programmed, fixed routes, and vans operating on a demand-response system with fixed pickup and destination points. We have not attempted to cost out a transit system with these elements, since the costs of AVs remains uncertain, especially for transit vehicles. We assume similar GHG emission reductions to the demand-response architecture described in the previous section. But we also note that autonomous vehicles today operate with "caretakers," drivers ready to take over should the technology malfunction. It seems safe to say that, once the technology reaches a certain level of reliability, caretakers will be eliminated. On the one hand, this should reduce labor costs; on the other hand, it means laying off bus drivers, unless other work can be found for them.

Were UCSC be able to acquire or purchase a small AV transit van, an initial pilot project, could be shuttling between the Main and Coastal Sciences campuses (Long Marine Lab), via Delaware, Swift and Western Drive (Figure 16). In several years, the new Coastal Biology Building at the "Coastal Sciences Campus" will be open, and the demand for intercampus transit will skyrocket. Testing of an on-demand AV along that route could prove (or disprove) the viability and suitability of AV at UCSC.

Figure 15a: Schematic waypoint map for DARPA robotic-vehicle "Grand Challenge"

Source: Douglas McGray, "The Great Robot Race," *Wired*, Dec. 2003, at: http://archive.wired.com/wired/archive/12.03/robot_pr.html (accessed 8/27/14).

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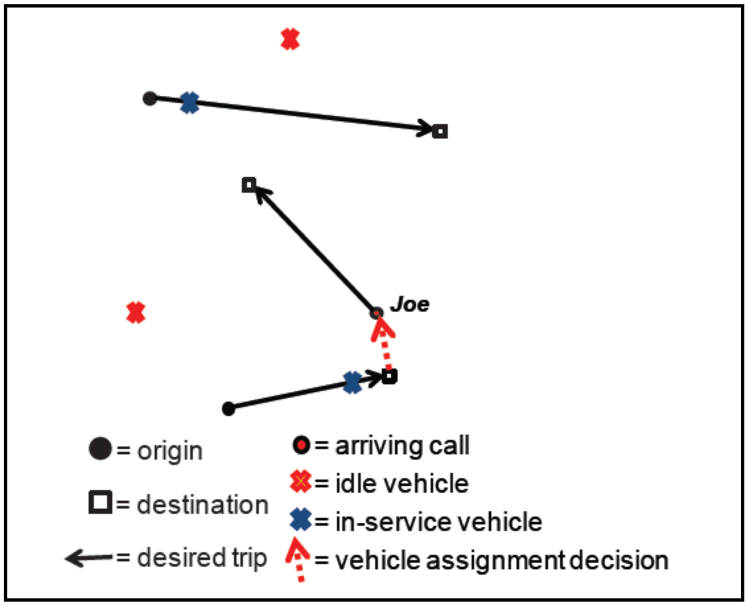
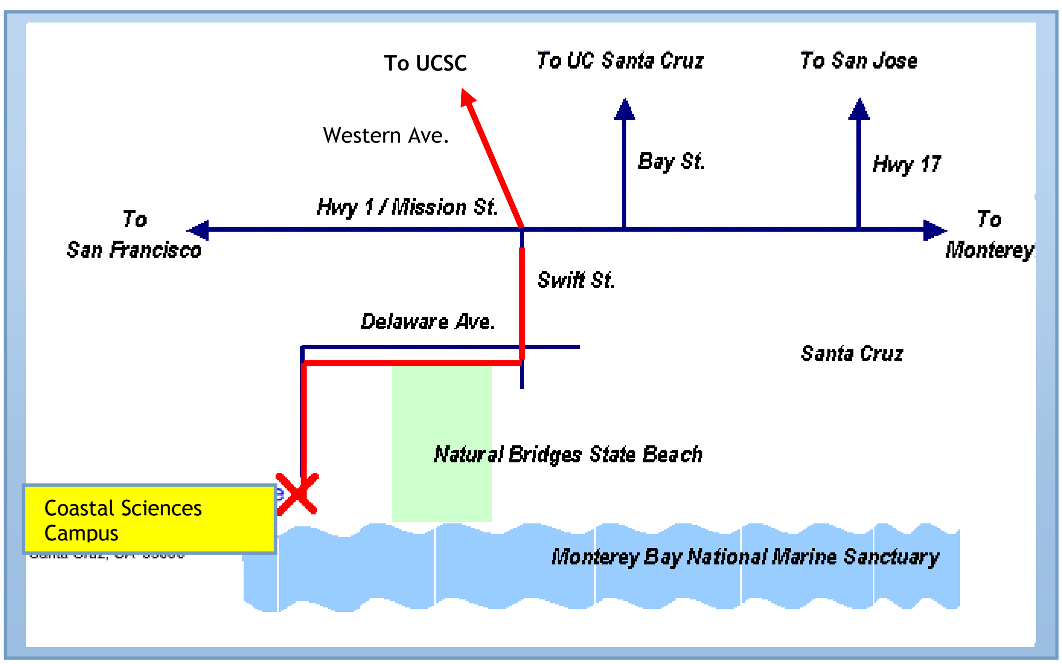
negligence. See John Villasenor, "Who is at Fault when a Driverless Car Gets in an Accident," *Atlantic.com*, April 25, 2014, at: http://www.theatlantic.com/business/archive/2014/04/who-is-at-fault-when-a-driverless-car-gets-in-an-accident/361250/ (accessed 8/27/14) and John Villasenor, "Product Liability and Driverless Cars," Washington, DC: The Brookings Institution, April 24, 2014, at: http://www.brookings.edu/~/media/research/files/papers/2014/04/products-liability-driverless-cars-villasenor/products_liability_and_driverless_cars.pdf (accessed 8/27/14).

Figure 15b: Operating algorithms for a driverless, demand-response system



Source: Lawrence D. Burns, William C. Jordan & Bonnie A. Scarborough, "Transforming Personal Mobility," New York: The Earth Institute, Columbia University, Jan. 27, 2013, p. 7, at: http://sustainablemobility.ei.columbia.edu/files/2012/12/Transforming-Personal-Mobility-Jan-27-20132.pdf (accessed 5/20/14).

Figure 16: AV route from Coastal Sciences Campus to UCSC Main Campus

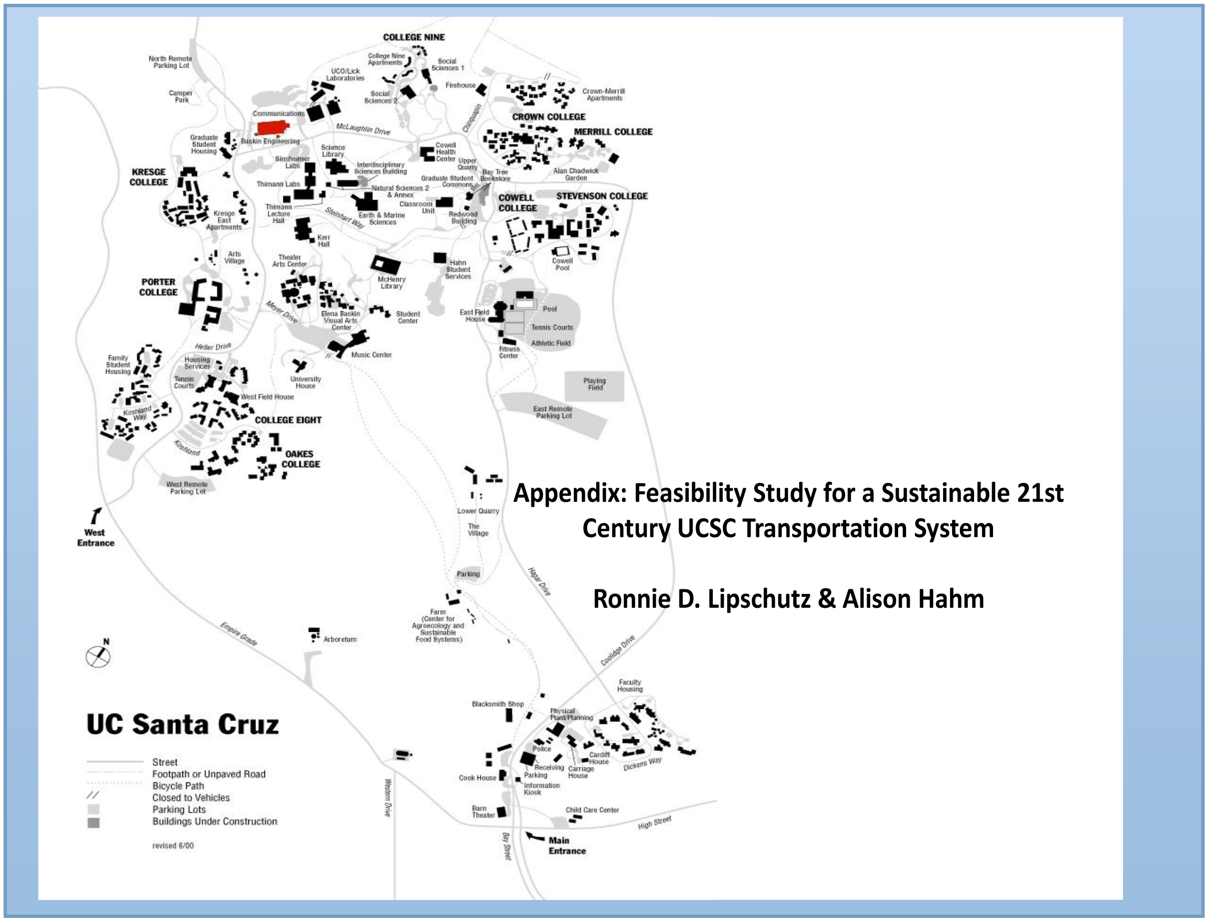


Source: http://ucsantacruz.ucnrs.org/reserves/younger-lagoon/directions/

XII. Conclusions & recommendations

Our initial goal in this study was to demonstrate the feasibility of converting the present campus transit system to either hybrid or all-electric operation, thereby reducing campus GHG emissions. Much to our surprise—but perhaps self-evident to anyone who has given the matter much thought—such conversion would have a very small impact on GHG emissions and, what's more, would not count for very much against the emissions that UCSC will be required to reduce (at least through 2020). The single, most-effective short-term step we could take to reduce University-associated emissions would be to reduce entry of single-occupancy vehicles to the campus. In this study, we have outlined several options for doing this without a loss of revenue to TAPS. We have also proposed some longer-term options for potentially increasing the efficiency of transit operations, which might reduce travel times for buses and vans, but which would have minimal impact on GHG emissions. There are excellent reasons for reconfiguring transportation to and at UCSC for the 21st century, because it would represent our commitment to sustainability and environmental protection and be key to long-term reduction of SOVs entering campus. As a next step, we recommend the following:

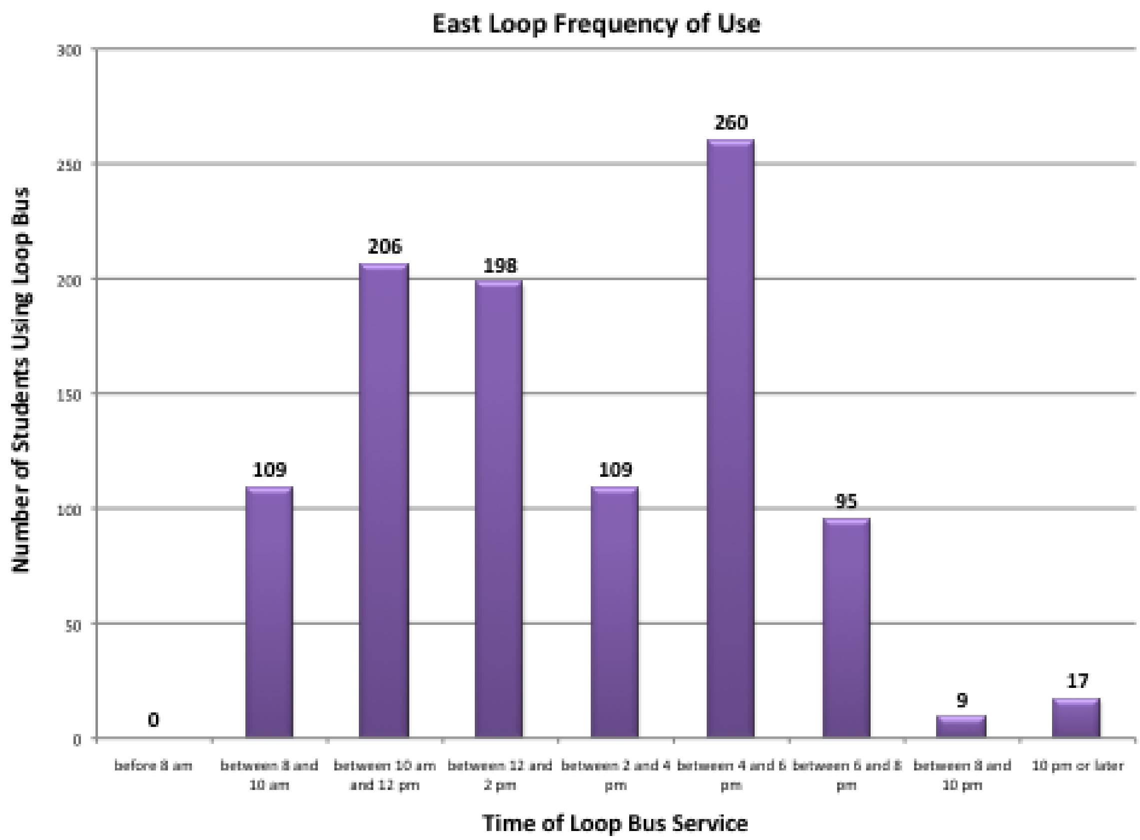
- Run express bus tests to determine whether they improve the "transit experience";
- Commission a more intensive study (or a revision of this one) that better analyzes options, their costs and benefits, and the potential for implementation;
- Develop and deploy, as soon as possible, a campus-run car-sharing program to reduce the number of SOVs entering the campus;
- In concert with this, raise parking permit prices to incentivize car-sharing and institute a means of returning fares to drivers in order to lower final permit cost;
- Investigate the requirements and feasibility of implementing an on-demand transit system;
- Seek to beg, borrow or steal HEVs, EVs and AVs for pilot programs and demonstration purposes.



UC Santa Cruz Loop Bus Ridership Survey: The purpose of the UC, Santa Cruz Ridership Survey is to improve the University Transportation Department's understanding of the seemingly "unpredictable" needs of student and faculty ridership. This feasibility study proposes that in analyzing UCSC Loop Bus ridership trends we can improve the schedule and general availability of the UCSC Loop Bus, to better suit the needs of UCSC students and faculty. Rather than viewing over-congestion or underused Loop trips as inevitable, this study views Loop inconsistencies as a problem to be solved.

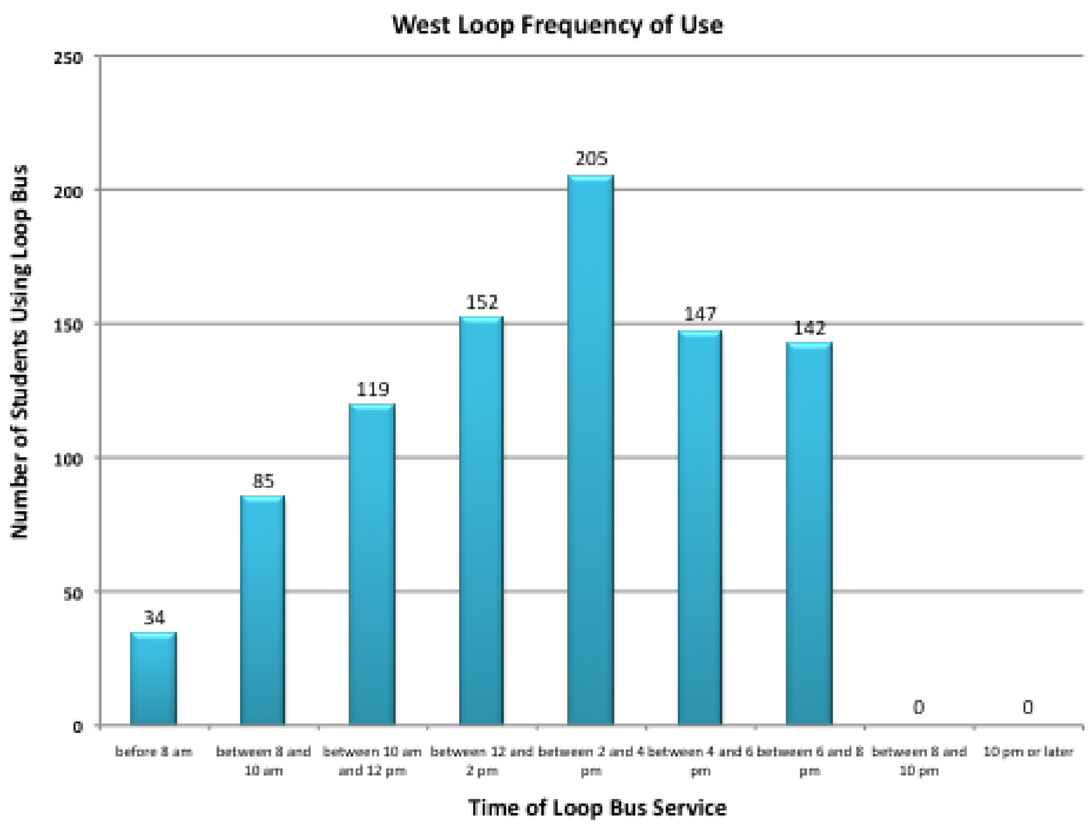
Scaling Ridership Data: The UC Santa Cruz Loop Bus Ridership Data was collected from a sample survey that has been scaled to enhance survey accuracy. The survey did not have the resources to reach all of the buses running within all surveyed hours. As a result, a sample from each service hour was collected. Just under 2,000 Loop riders were recorded boarding and exiting the Westbound and Eastbound Loop. The Eastbound Findings record 1,852 riders boarding and 1,692 riders exiting. The Westbound Findings record 1,893 riders boarding and 1,786 riders exiting. Compared to the UC Santa Cruz Ridership Survey from 2012-2013 this is roughly ⅓ of the standard Rate of Ridership Usage. Thus, to improve survey accuracy, Eastbound and Westbound Pivot-Tables were scaled (x3) to realistically reflect the activity of all students using all running loops during the period of time that the individual surveys took place. From this qualified data, the Eastbound and Westbound Pivot Tables reveal unique patterns of Loop Bus Stop overuse and underuse.

Pivot Table: The Eastbound and Westbound Pivot Tables, for the Survey Report, reflect the total activity that was recorded on each surveyed Loop. This Loop activity is categorized as "On" and "Off" data. This data summarizes the rate at which students depart from the Loop at a specific stop and as well as at what rate students use particular stops to board the Loop. In understanding how specific Loop-stops are used, one can sort overused stops from underused stops and visa versa. Furthermore, understanding the rate of specific stop-use allows the UCSC transportation department to categorize points at which the UCSC Loop is unnecessarily running, and at which point the Loop is in need of added support to cope with overwhelming ridership demands.



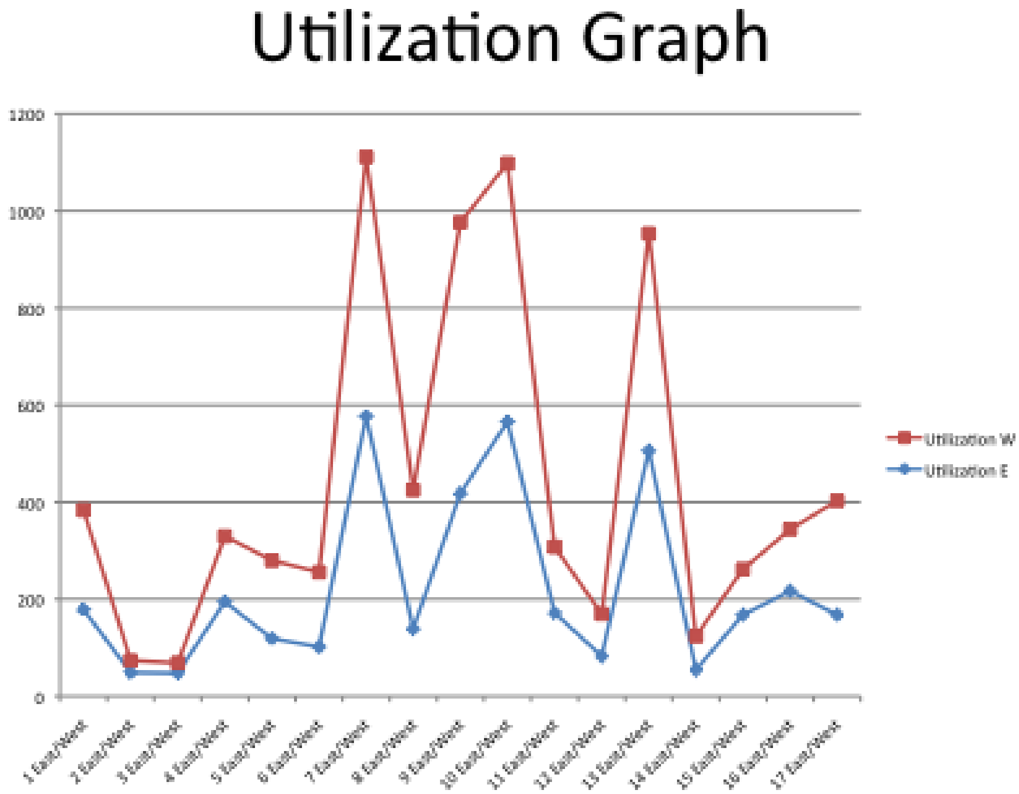
Eastbound Loop Trends: The Standard UCSC Loops follow a consistent route based on a 15-minute fixed "loop" circling campus, disregarding traffic congestion and shifting ridership demands. From the most recent UCSC Loop survey results, The Eastbound Loop shows two major peaks: between 10-12 PM and 4-6 PM. The first peak begins as a gradual incline, rising from 7-10 AM and peaking at 10AM-12 PM. Meanwhile, a sharp decline from 12-2PM precedes a rapid increase in use from 2-4 PM. The final period from 4-6 PM declines in use until the termination of the Eastbound Loop.

Why: The distinct peaks shown in the Survey Graph and within the Survey Data-set provides a valuable insight that captures the nature of Eastbound Loop traffic and ridership demands. A possible explanation is that students on campus who have class Afternoon and Early Evening use the Eastbound Loop. Using the Loop consistently twice a day explains the two clear peaks. A second explanation is that the Eastbound Loop buses are frequently used to travel to and from permitted parking spaces, which would cause two sets of peaks (student and faculty departure to classes during the Afternoon and departure from classes to the Parking Lot early evening).



West Loop: Unlike the Eastbound Loop, the Westbound Loop's ridership data models a single peak. Starting from 7 AM, the West Loop use gradually increases and peaks between 2-4 PM. From 4-8 PM, the West Loop usage experiences a ridership decline which continues until termination.

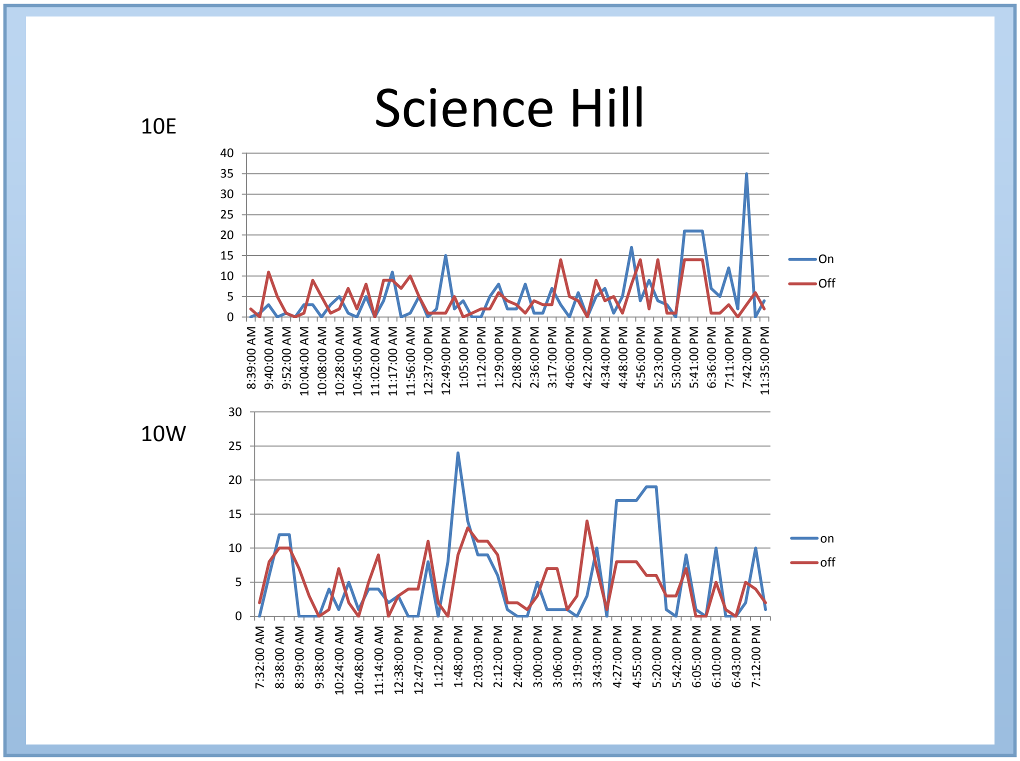
Why: Opposed to the Eastbound Loop, the Westbound Loop has one peak probably due to the majority of class schedules and general student needs on campus. Furthermore, Noon is a peak time for lunch, traveling from morning class to afternoon class, and use of campus facilities before morning class and before evening class.



Utilization Graph: Building on the initial Pivot Tables, the UCSC Loop Survey Report condenses the original data into one collective Utilization Graph. The Utilization graph symbolizes the total activity that took place at each loop stop by combining the on and off data into one data-point. Thus, the "on" and "off" data that was recorded during the traffic flow is summed and graphed in order to comparatively represent underuse and overuse for Eastbound and Westbound Loops. Moving away from how riders use individual stops, the utilization graph represents total use.

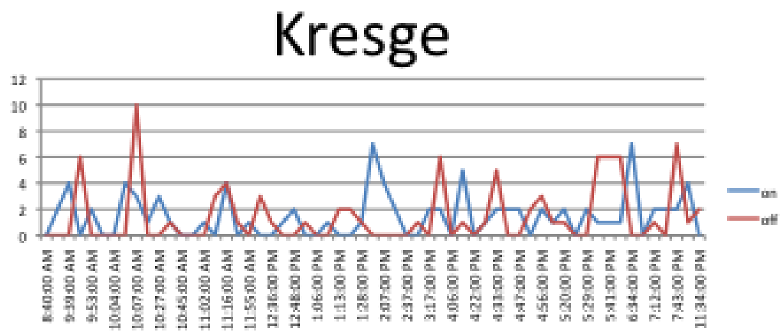
Conclusion: The purpose of this survey is to understand UCSC Loop Bus usage to create a more intelligent transportation system on campus. This Ridership Survey proves the need to streamline UCSC Loop Bus infrastructure to amend shortcomings. In understanding the source of these shortcomings, this analysis aims to aid in the creation and refinement of an Express Shuttle System. This Shuttle System will more effectively serve the needs of the campus by instantaneously responding to increases during Peak Service Hours. The Express Shuttle will also serve as an efficient substitute for the Loop during periods of reduced activity to prevent unnecessary Loop Trips. Investing in an Express Shuttle will increase travel efficiency, reduce costs, and help the campus to reach the new AB32 permitted carbon limits.

Individual Stop Trends for Loop:

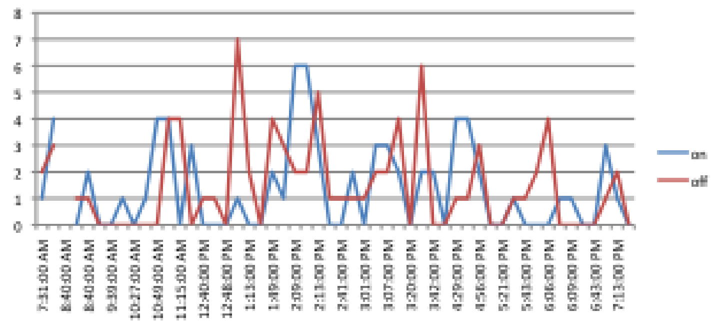


Science Hill is the second most frequented stop used equally as a point of getting on and off the Loop. The Eastbound Science Hill Survey records 885 riders per day getting on the loop at Science Hill and 813 getting off. The Westbound Science Hill Survey records 831 riders getting on and 765 riders getting off. Science Hill serves as a central location for Science and Engineering classrooms and labs, the Science & Engineering Library, Baskin Lecture Hall, and a public parking structure. Parking is limited and can be expensive around this part of campus, so regular use of individual cars is infrequent. The most accessible routes to Science Hill appear to be the Loop Bus and the Santa Cruz Metro. Thus, it is no surprise that Science Hill faces high ridership demands, and is often impacted as a result.

11E

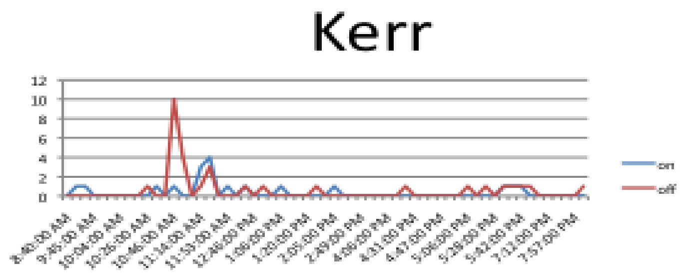


11W



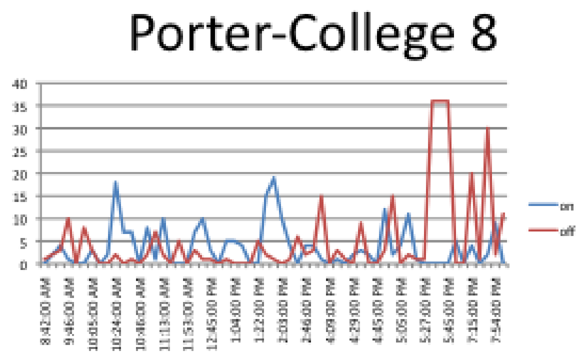
Kresge: The Kresge bus stop follows directly after Science Hill. The same Ridership Survey Records less than half the rate of ridership use for the Kresge stop. The Eastbound Survey records 261 riders getting on and 255 riders getting off. The Westbound Survey records 210 riders getting on and 228 riders getting off at Kresge. Like Science Hill, Kresge has a symmetrical amount of students getting on and off. Kresge's reduced ridership suggests that the Kresge stop is used primarily for Kresge residents.

12E



Kerr Hall: The Ridership Survey of Kerr Hall exposes a disproportionately high amount of students getting off the loop opposed to getting on the Loop from the Kerr stop. The Eastbound Survey Results records 54 riders getting on and 90 riders getting off. The Westbound Survey Results records 54 riders getting on and 207 riders getting off. Rather than using Kerr Hall as a loading zone, it seems to be used as a departure point.

13E



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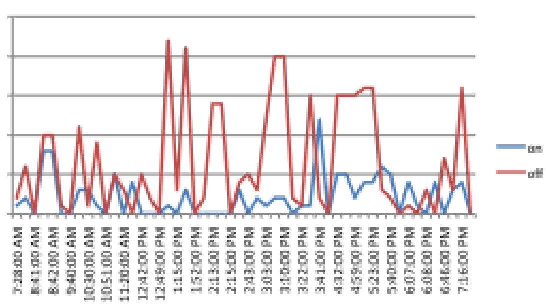

College Eight functions as the third most frequented stop. The Eastbound Survey Results records 636 riders getting on the loop and 882 riders getting off the loop at College 8. The Westbound Survey Results records 330 riders getting on the loop at College 8 and 1,011 riders getting off the loop over time. The two College 8 stops are essentially bus stops for College 8 and Porter. Needless to say, the high frequency of use demonstrated at College 8 disrupts the Standard Loop Schedule, causing TAPS to commission multiple Loops to compensate for overwhelming ridership demands.[46]

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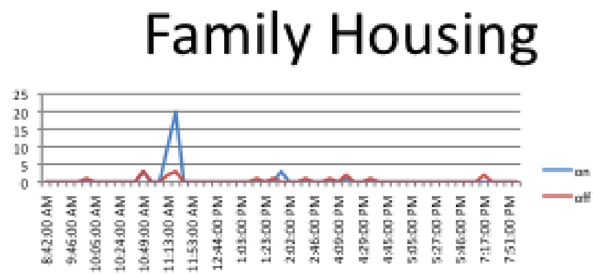
[46] Extreme peaks throughout the day at the Main Entrance is often supplemented by a second loop bus that typically fills to only ¼ - ½ capacity that runs close behind the impacted loop. The supplemental loop often runs empty after a single loop. To conserve energy and reduce carbon emissions, we may remedy impacted Loop trips by supplementing loops with energy efficient Express Shuttles that can park at charging stations and depart at will.

14E



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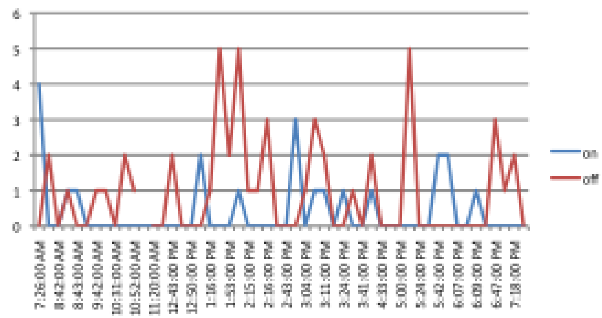
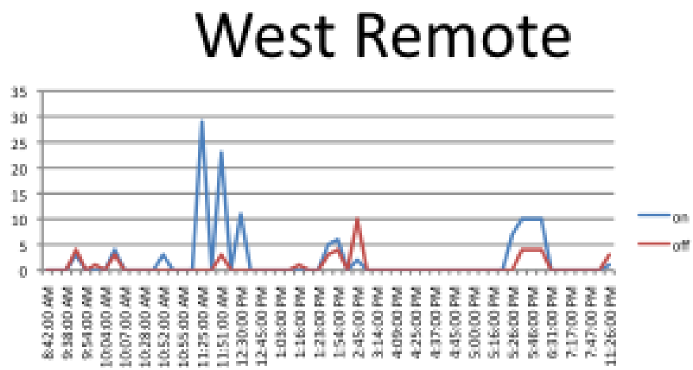


Family Housing: The Family Housing stop predictably triggers a decline in use, due to the smaller population of faculty and students living in Family Housing. This area of campus is also relatively isolated from the surrounding university departments and community resources. The Eastbound Survey Results record 111 riders getting on the loop and 54 riders getting off the loop at Family Housing per day. The Westbound Survey Results record 63 riders getting on the loop and 144 riders getting off the loop.

15E



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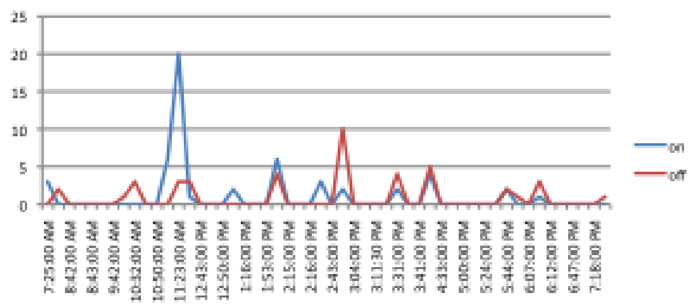
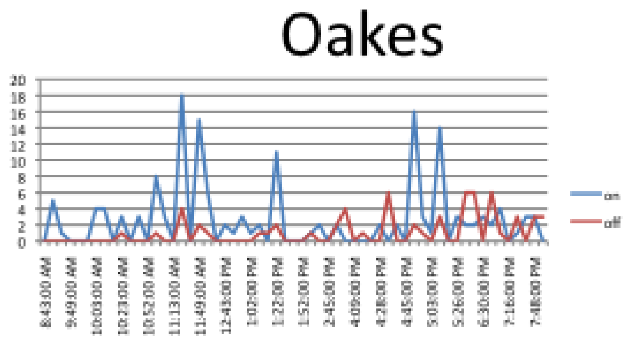


West Remote: Ridership frequency more than doubles approaching the Eastbound West Remote Loop Stop, which interestingly reveals a significantly higher amount of students loading on the bus than departing from the bus. The Eastbound West Remote Survey records 372 students getting on and 132 students getting off. The Westbound West Remote Survey records 156 students getting on and 126 students getting off. The West Remote Lot and Oakes both offer student parking lots, and permitted spaces. The amount of students getting on the loop from this stop could be a result of the amount of students parking their vehicles, and using the Loop to navigate campus. Meanwhile, students who live within others areas of campus would not need to travel back to the West Remote stop, only students traveling back to retrieve their vehicles, and those that live in the surrounding student housing.

16E



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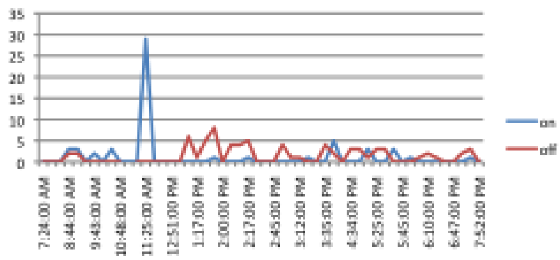
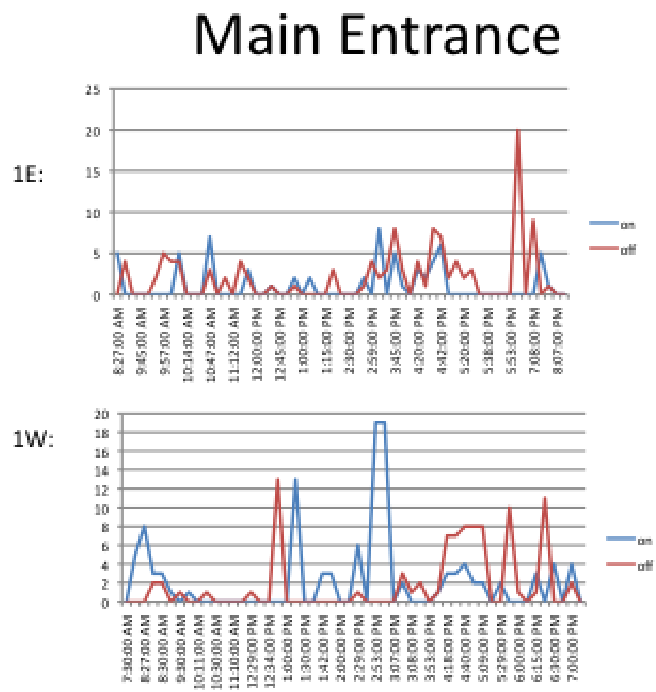


Oakes: Similar to the West Remote lot, the Eastbound Survey Results for Oakes records 468 riders getting on the Loop and 183 riders getting off the Loop. The Westbound Survey results records 168 riders getting on the loop and 213 riders getting off. The same trend of students getting on the Loop at Oakes could be due to the large student parking lot that is beside Oakes Student Housing.



Main Entrance: The Eastbound Main Entrance Survey Results records 333 riders getting on and 171 riders getting off the loop. The Westbound Main Entrance Survey Results records 342 students getting on the bus and 273 students getting off. The Westbound and Eastbound loops reveal very different stop trends for the Main Entrance. The Westside Main Entrance is used primarily as a point to get on the loop, while riders get off the Main Entrance East considerably more than those that board. Two hypothetical explanations are: 1) Main Entrance East feeds into the Apartments that run parallel to the Loop Route 2) Main Entrance East feeds into the Metro Bus Stop that continues on Bay, directly across from the Loop stop.[47]

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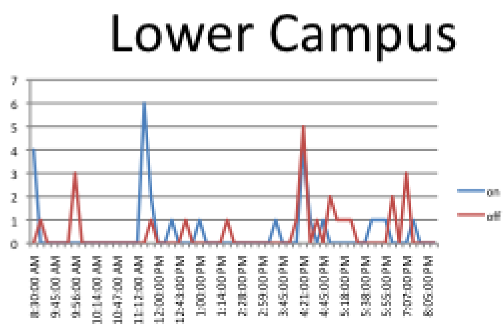
[47] If the East Main Entrance is being used as a linkage point to the Metro Bus Stop, it is possible that there would be ridership interest in a supplemental shuttle system that would easily circumvent the standard Loop trip, taking students and faculty directly to the base of campus, cutting down on impacted loop routes, and reducing wait-time on Loops as well.

2E



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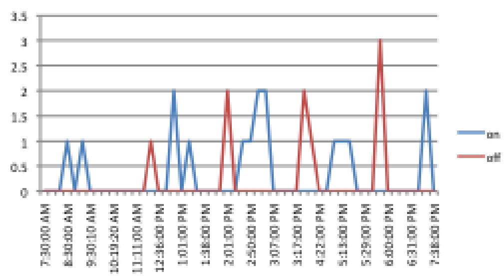

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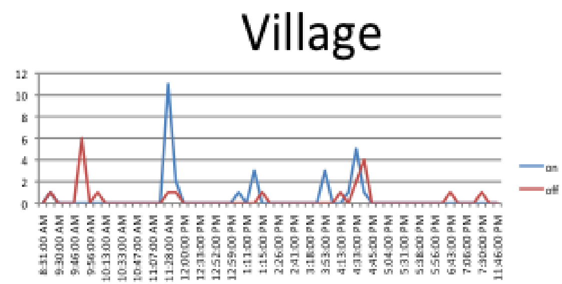

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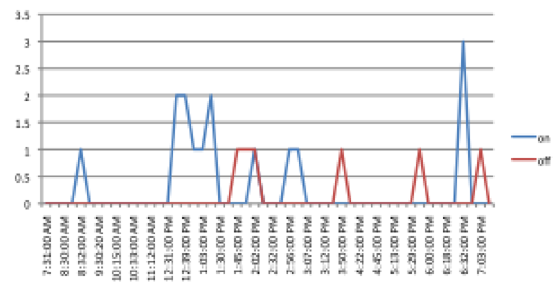
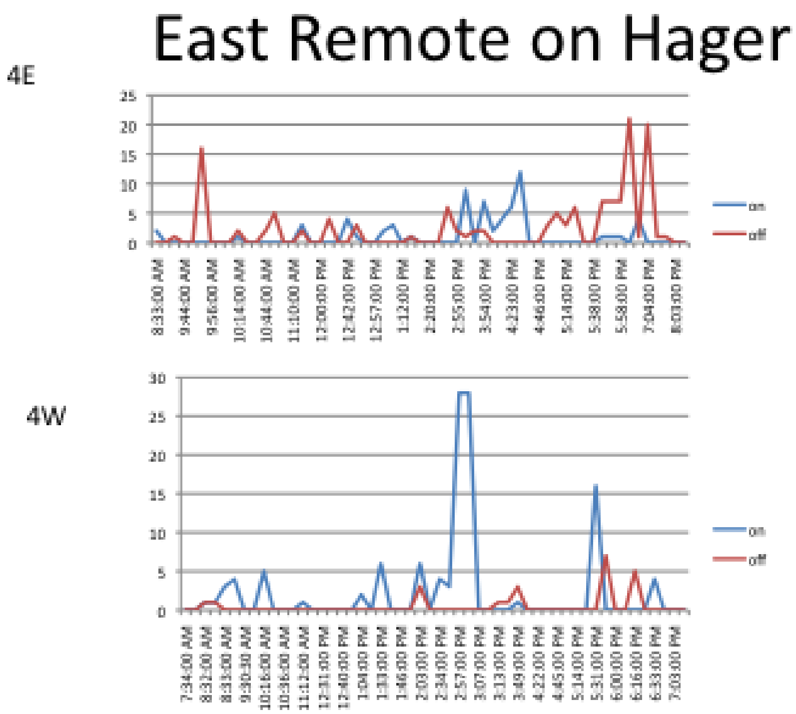
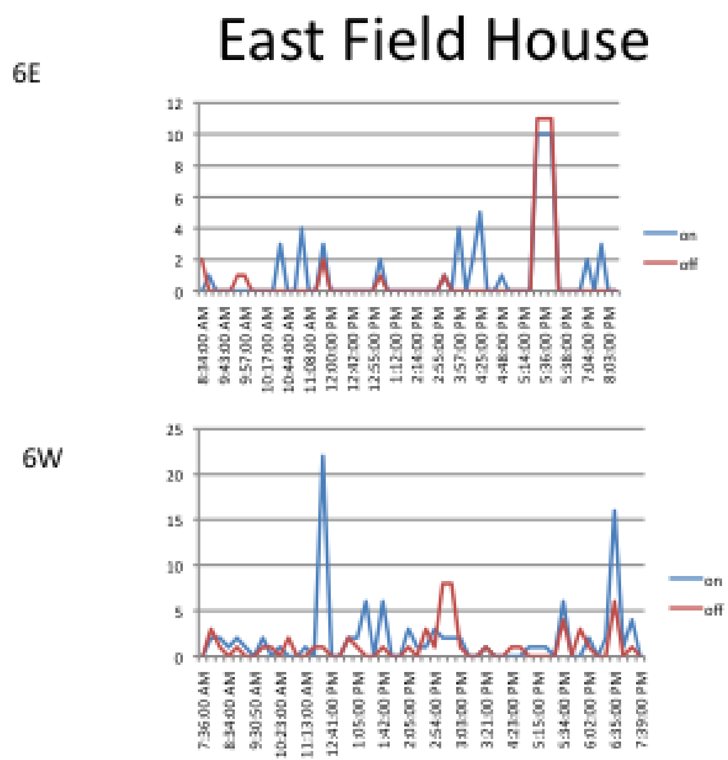


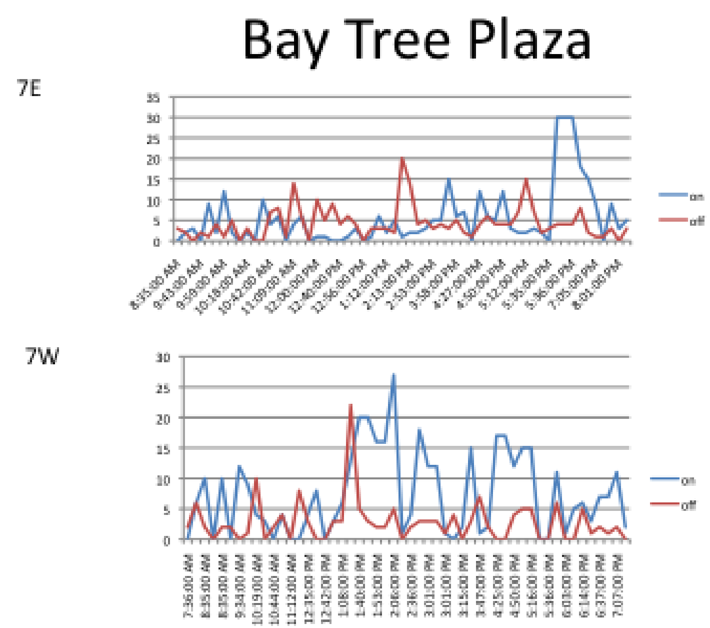
Lower Campus & Village: The Eastbound Ridership Survey Results records 75 riders getting on the loop and 72 riders getting off at Lower Campus. The Westside Ridership Survey Results records 48 riders getting on and 21 riders getting off at Lower Campus. The Eastbound Survey records 84 riders getting on at the Village and 60 riders getting off at the Village. The Westbound Survey records 45 riders getting on and 18 riders getting off at the Village. Both Stops show a certain dip in ridership usage compared to the Main Entrance.



East Remote on Hager shows incredibly imbalanced data. The Eastbound Survey results reveal a total of 192 riders that get on and 393 riders that get off the Loop over time. Similarly, the East Remote in Lot shows a similar problem: the Survey records 282 riders getting on and 75 riders getting off. Imbalanced ridership usage often results in Loops unnecessarily taking time to service stops that are unlikely to be used.

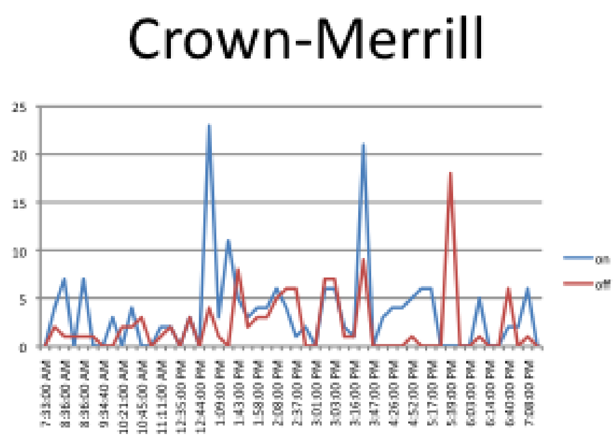


East Field House: The Eastbound Survey Results records a relatively balanced dataset of 183 riders getting on the loop and 123 riders getting off the loop, which can intuitively be explained by students traveling to the East Field House for Physical Education classes and those using the East Remote Parking Lot.



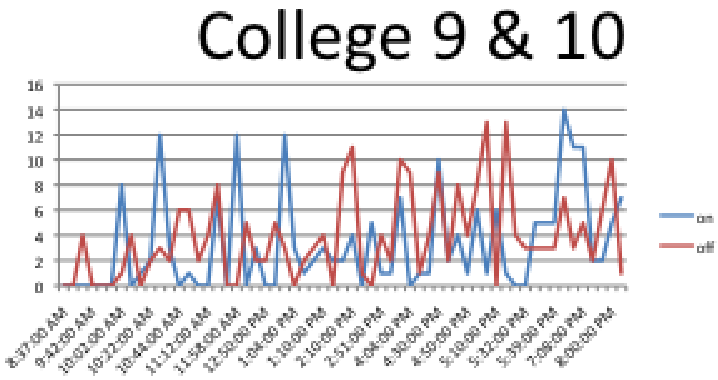
Bay Tree Plaza: The Eastbound Survey Results for the Bay Tree Plaza records the largest spike in ridership yet, 972 total riders loaded on the loop throughout the day, and 759 total riders departed from the loop. The Westbound Bay Tree Plaza records 1164 riders getting on and 438 riders getting off. Needless to say, Bay Tree Plaza is an impacted area of the campus that neighbors McHenry Library, the Computer Labs, and the Bookstore. Often, crowds of students are seen waiting for Buses that frequently, are so overloaded that students are left stranded.

8W



Crown/Merrill has only one Bus Stop along the Westbound Loop. The Survey records 531 riders getting on the Loop and 327 riders getting off. Most residents of Crown/ Merrill use the Loop Route to travel around campus, which makes sense why there is a greater amount of riders getting on the Loop at Crown/Merrill, than getting off.

9E



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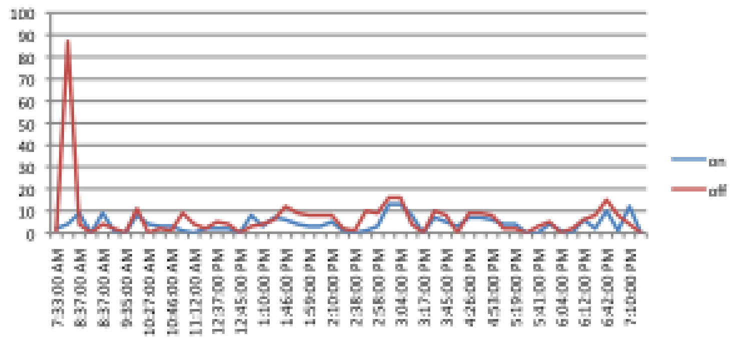

College 9 & 10: The Eastbound Ridership Data records 576 riders getting on and 678 riders getting off. The Westbound Ridership Data records 621 riders getting on and 1053 riders getting off. The Surveyed Data records a very high rate of riders getting off compared to those getting on. This type of ridership discrepancy suggests a need for an alternative system of transportation; an Express Shuttle Supplement could replace Loop Buses during underused service hours to prevent associated waste.