Engineering Sciences 96

Parking at Harvard: Addressing New Demands Associated with Campus Development

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Foreword

This report is the work of ten, mostly junior year, students enrolled in a Harvard University course entitled *Engineering Sciences 96 - Engineering Design Projects* in the spring term of 2001. It is our experience that design cannot be learned in the abstract. In most instances, a designer learns by doing and by profiting from mistakes and false starts. The aim of Engineering Sciences 96 is to help our engineering students learn about the design process by providing them the context and opportunity to undertake an extended, integrated and supervised design experience. The course is structured as a design seminar in which students work as a self-directed team on real world design tasks defined by interested "client."

We have been very fortunate to have as our client this year Thomas E. Vautin, Associate Vice President for Facilities and Environmental Services, in his capacity as chair of a task force created by the Harvard central administration to look into a range transportation management issues. In presentations on February 5th and 8th of this year, Mr. Vautin and his associates, Elizabeth Shephard, and Jennifer Champa, outlined the scope of issues associated with impact of campus development in Cambridge and Allston on the University's parking supply. Following these presentations students met individually with other members of Harvard's University Operation Services (UOS) group to further refine their understanding of the problems facing Harvard. In the design phase the students widely consulted local experts, interested venders and literally searched the globe for proven technologies. Throughout the design process, the students have organized themselves and determined how they would address various issues and we, the course instructors, have acted as coaches and critics.

This report is a somewhat expanded version of the public presentation the students made on May 7, 2001 to Tom Vautin and his associates, several faculty members from Harvard's Division of Engineering and Applied Sciences, and other guests. The proposals presented include means to decrease the demand for parking, to increase supply in areas where that is possible, to use modern proven technology to increase the utilization of available spaces and to decrease costs of any planned parking structures. The most radical proposal is a recommendation that Harvard consider the use of automatic parking structures as a cost-effective means of implementing underground parking.

While this is a report written by this year's Engineering Sciences 96 students, we, the faculty advisors, concur quite generally with their recommendations

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1 INTRODUCTION

This year's Engineering Sciences 96 design workshop was charged with looking at Harvard parking. In our exploration, we have taken as given that Harvard does not plan to acquire any new land in Cambridge! There is, however, a pressing need to find space for new facilities to accommodate expansions necessary to keep Harvard on the leading edge of the academic universe. Consequently, the University must make the best possible use of the land it already occupies in Cambridge and, in particular, the amount of space committed to surface parking must be reduced in spite of a growing demand for parking. The construction of surface parking structures is not an option since Harvard is committed to preserving the prevailing character of the campus and adjacent residential areas. Thus, the University is faced with a precarious parking problem; as it expands, it is left with a shortage of parking. The parking situation was not always this challenging.

The decade of the 1950's was an uncomplicated time to be a commuter at Harvard. Commuters driving to work or class would find the task of locating an available parking space easy to accomplish. Parking was widely available at the Radcliffe Quadrangle as well as near the River Houses and the Law School. Even graduate students could find parking.

However, in the beginning of the 1960's, the situation became a little more difficult, and Harvard's current parking problem was born. It was during this era that Harvard sustained a tremendous period of campus growth within the Faculty of Arts and Sciences and other schools. The result was an influx of talent, both student and faculty, and there was a corresponding increase in the portion of campus space occupied by buildings. The expansion left the University's growing number of commuters with fewer options. Pound Hall, Mather House, and Leverett and Quincy House extensions were all built covering old parking lots. Ironically, during this period the number of cars on the road nation-wide increased with the boom of interstate highways, a trend reflected in Cambridge.

When the economy slowed in the 1970's, Harvard's expansion slowed as well. Although the number of faculty at Harvard remained nearly constant for the decade, the number of driving commuters increased significantly. Parking was no longer a simple consequence of the daily commute. The result of this parking scarcity, much like we see today, was an increase in parking fees - a modest disincentive to park.

The germ of a new parking approach appeared in 1984: remote parking. It was at this time that the Red Line was extended beyond Harvard Square, out to Fresh Pond. The Alewife Station opened as a terminus for Boston and Cambridge bound commuters. With direct access to both Routes 2 and 16, and an adjacent 2,000-car garage the Alewife T Station became a major transportation portal. While Harvard's growth remained relatively static, remote parking became a potential accommodating solution.

Neil Rudenstine became the twenty-sixth Harvard President in 1991 and before long the University kicked off its largest fund raising drive in history. The campaign's success has allowed for the construction of new buildings in the North Campus Precinct such as Naito, Bauer and Maxwell-Dworkin. Although much needed, these new buildings and other planned constructions are eating up the ground previously occupied by surface parking lots. The removal of these smaller surface lots necessitates the building of new parking structures.

Harvard has chosen to place the new parking structures underground. While this solution may maximize surface space available for facilities, and preserve campus green space, it is very costly. Current figures suggest that the parking will cost something like $60,000 per space! The University has set out to find other means to alleviate the burden of fulfilling commuters' parking needs. If for no other reason, these alternate solutions will lower the number of spaces that must be built, at such an astronomical cost.

1.1 Background Data

Harvard University has 12,015 employees who live in Massachusetts and work on the Cambridge and Allston campuses. They live as far west as Springfield, but the majority live within the I-495 circle. The Harvard Parking Office issues 3,328 permits and assigns a parking lot on campus to each permit. A parking permit guarantees its holder a parking space, although not necessarily in their assigned lot. If a lot is full there are overflow lots where commuters can park instead. Many commuters leave early for work so that they will arrive in time to get a space in their preferred lot and not have to drive farther to overflow lot.

Parking permits will cost $450 per year for the 2001-02 academic year. That works out to $37.50 a month which compares favorably with the monthly cost of parking at commercial lots in Cambridge. In addition to these 3,328 parkers, 1,280 students (mostly graduate students) hold parking passes. These 4,608 parkers are assigned spaces in 82 lots in Cambridge and Allston managed by the Parking Office. Many of them do not park in their preferred parking lot, - *i.e.,* those closest to where they work. Parking places are assigned on a first-come-first-serve basis and most waiting lists for spaces are 3 or more years long.

The lots provide 5,682 spaces, of which 3,170 are in Cambridge. Most of the spaces in Cambridge are next to buildings, and can be thought of as "desirable" in terms of short commuting times for the people who park there. The other important attribute of the Cambridge spaces is that they are "local" as opposed to "remote." In this report "remote" parking refers to parking outside of Cambridge that requires shuttles to get commuters from the parking lot to their workplace. Shuttles are problematic since commuters will not use remote spaces if the shuttles do not run frequently or efficiently. Obviously shuttles have initial and upkeep costs associated with them, as well as scheduling and routing issues.

These numbers do not seem worrisome at first. There are over 1,000 spaces available to the Parking Office which are not assigned to any parkers. So what is the problem?

Harvard is planning construction that will take place partly on existing surface parking lots. Overall, this construction will eliminate 2,100 parking spaces. Elimination is more than an inconvenience for Harvard: parkers. Cambridge city ordinances set the number of parking spaces required for buildings based on floor space and various other factors. These laws also require that spaces assigned to buildings be within one mile of their building, so it will not be possible to build more parking spaces in a remote site in, for example, Watertown, and bus people to work. These 2,100 displaced spaces must be put underground.

Putting 2,100 parking spaces underground at $60,000 per space will cost $126 million. To put that cost in perspective, it is an enough money to send 1000 undergraduates, almost two thirds of a class, through four years of Harvard on full scholarships! Harvard also puts a high value on its green space. All other things being equal, the University would favor relocating another 1,500 spaces underground in order to better use the space they occupy now. That would mean an additional $90 million dollars, which would put another 1660 students through school. Thus, the amount of money Harvard might spent to put parking underground would be enough to completely educate an entire class!

In order to determine how best to free up parking spaces and streamline existing lots we looked at the people who park (see table below). Of the people who park, 51% are administrators of some sort. They work fixed hours, which means that they are all likely to arrive around the same time. 22% of the parkers are faculty, whose schedules tend to be less constrained since class times vary from day to day. Casual surveys of faculty showed that this generalization was fair, some days they might stay late and other days they seem to leave for home at around 2:00 pm. We were also told at the outset of our project that faculty access to inexpensive parking was an important incentive and that in order to be competitive with other schools in hiring top faculty, it is a bonus to be able to provide convenient parking. Another 25% of the parkers are hourly employees, and the last 2% are teaching and research fellows. The data is most instructive when viewed in terms of parkers who live within a mile of campus. Of these, only one third are administrative. The percentage of hourly employees, 19%, is roughly the same, but the fraction of faculty is now 40%.

	All Parkers (3,328)	**Parkers living within 1 mile (13%)**
Administrators	**51%**	**33%**
Faculty	**22%**	**40%**
Hourly employees	**25%**	**19%**
Others	**2%**	**8%**

Our group judged the one mile radius an acceptable walking distance for commuters and so we have used that distance to identify a subgroup for whom walking is a commuting option. Study of this subgroup also gives some indication of how commuting patterns changed as people moved closer to Harvard. Of the quarter of the total employees who park, 13% live within a mile of campus. As we move out of Cambridge that density decreases significantly: only 19% of parkers live within 5 miles of campus. The one-mile radius therefore represents the highest density of parkers.

Of the 3,300-odd employees who park, only 9% have public transit passes. The 13% who live in walking distance could walk when they chose not to drive and so not show up in this statistic. The remaining 87%, however, have little interest in using alternative commuting methods, even though Harvard provides a subsidy to buy public transit passes. This would not seem significant if these people were driving from places with only road access, but that is not the case. Of commuters who drive, 80% live within three quarters of a mile of a bus or subway route. An additional 4% who are near neither bus nor subway live within three quarters of a mile of a commuter rail line. With so many parkers able to take public transit, it would be a great boon to Harvard if they could be encouraged to do so.

1.2 Current Harvard Planning

The number of cars in and around Harvard Square has increased dramatically over time, and it will continue to increase with Harvard expansion in the future. The crowded streets of Cambridge must accommodate the city residents, the university population and through traffic. The University has no intention of increasing the number of its total parking spaces in Cambridge. Instead, it is opting to relocate existing parking spaces, as surface parking lots are replaced with new facilities.

Clearly, the University has embarked on a complex and costly undertaking as it seeks to maintain its status as a leading center of research while keeping most academic activities clustered in Cambridge. New academic facilities will be constructed and new construction will increase demand for parking as more people take jobs within the Harvard community. As stated earlier, there is already a 3-year waiting list for some lots. However, construction will decrease supply as new buildings go up over existing surface spaces. The University has already begun implementation of a very expensive plan to resolve this balance.

Over the course of future construction, the University intends to remove surface parking, as space is needed for new facilities. As surface parking is removed, and more parking is needed with new construction, underground parking will be built at a cost of roughly $60,000 per space. For comparison, an above ground parking structure (based on the cost of a structure under construction by MIT on Albany Street) would cost only $19,000 per space.

1.3 Requirements and Issues

To minimize the use of aboveground space, Harvard has chosen to build underground garages as their tool for balancing the current parking demands. Any future parking expansion is planned for outside of Cambridge. While expensive, this appears to be the simplest solution. However, during all new construction, Harvard must subject itself to all relevant Cambridge ordinances and maintain a amicable relationship with the Cambridge community.

Some Cambridge ordinances are set out specifically to control the number of cars driving in the Square. Harvard is committed to compliance with these ordinances when building or maintaining any lots, however, the University is trying to prevent the building of any unnecessary new spaces.

Harvard, while maintaining their own policy of not wanting to increase the number of parking spaces in Cambridge, is still subject to the Parking and Transportation Demand Management Planning Ordinance. It states that no one is allowed to expand any non-residential lot without first clearing it with the zoning commission.

The University expends considerable effort to remain on good terms with the surrounding Cambridge community. For example, on Hammond Street residential structures are limited to 35 feet in height. In light of that, Harvard University has agreed to limit building directly across from this residential neighborhood to two stories in height. The University necessarily must conform to architectural standards set by buildings already existing in that area. Once complying with these standards, the University can begin to plan their new facilities and the impact they will have on the surrounding community, especially on local parking.

1.4 A Demand-Supply Approach to Harvard's Packing Problem

Our class has been given the challenge of developing a new perspective on parking solutions. We were asked to look beyond simply the economics of the problem, as might be expected of engineering students. The class identified the problems, brainstormed many solutions, evaluated them all, and evaluated in depth the most promising ones.

Our investigation for parking solutions led us to many different directions. We recorded the time, to the minute, of all vehicles entering and leaving the DEAS/Littauer parking areas. The DEAS/Littauer became our "test lot" for any modeling we found necessary within our research. To properly model commuter behavior and traffic flow for the test lot, we made use of computer programming. While exploring new technologies, we researched different vendors and contacted them to acquire detailed information about their products. One member of the class traveled to Germany to get a first hand look at new parking technologies. We took advantage of the services within campus, receiving help from ID Card Services, the Harvard Parking Office and many others. We believe that we have found novel, feasible solutions to enhance the Harvard parking system.

Early in our investigation, we resolved that the key to a successful plan would involve using a multi-track strategy to optimize a balance between the supply of parking spaces and the demand for them.

To solve demand-side solutions, we needed to devise a system promoting incentives to decrease the number of single occupancy vehicles traveling to campus, improving upon the recently created CommuterChoice program. These include any enticements to decrease the number of spaces needed by making it cheaper and more convenient to use alternative means of transportation. The use of web-based information services is another way to help entice commuters from coming to work in single occupancy vehicles. Web services help to streamline processes, which would normally require human attention. These services greatly increase the efficiency of the ridesharing program.

At the other end, to deal with supply-side solutions, the University has already prepared itself to spend roughly $60,000 per space to move all parking underground. To alleviate some of that astronomical cost, we have tried to increase efficiency of current surface parking and make the most of the little space that is already available.

As mentioned earlier, parking enforcement is a significant problem across campus. On average, one in seven parkers in the test lot were found to be illegal parkers, however, only 32% of parking tickets are paid. Implementing access control at lot entrances can eliminate illegally parked vehicles that would take spaces away from legitimate parkers. Access control also provides detailed information on lot usage, allowing for permits to be assigned more efficiently. However, as surface parking is removed and replaced by University expansion, remote or underground garages must be constructed as a replacement.

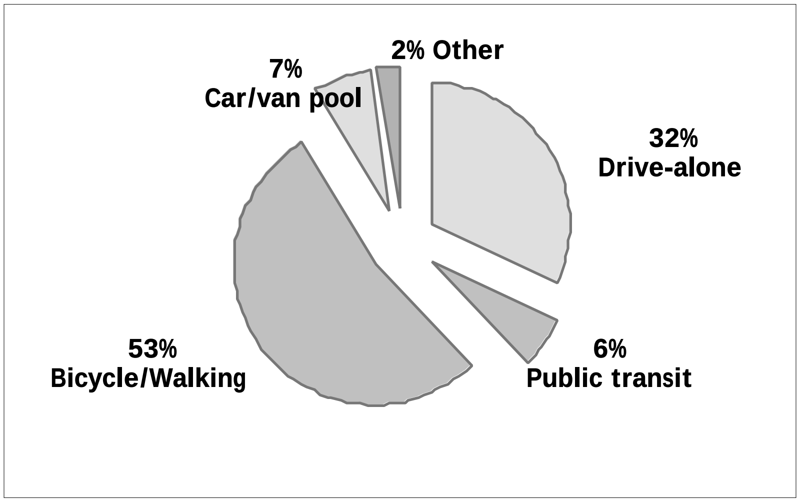
New parking technologies allow for more cost-effective use of this underground space. These technologies often allow an increase in parking density within a particular location. This report will allow us an opportunity to share with the Harvard community what we have learned and what we recommend.

Many drivers consider driving to work everyday a natural right as part of their job. It is a very difficult thing to get them out of their car, or to bring another person along with them on their commute. To try and cut down on the number of single occupancy vehicles traveling to campus, Harvard has begun to devise a system of incentives to lure people into other modes of transportation. We begin our detailed discussion with a presentation of our recommendations for enhancements in the current incentive programs.

2 TRANSPORTATION DEMAND MANAGEMENT AT HARVARD

Harvard's location in Cambridge is doubtless one of its chief attractions. However, the attractiveness of the campus and community are in several respects mixed blessings. Harvard is surrounded by appealing, largely residential neighborhoods, but housing is scarce and expensive so that many Harvard employees must commute from a distance. The beauty of the campus is renowned, but preserving that beauty within existing spatial bounds significantly limits the possibilities for expansion of academic programs. Parking and traffic congestion are ever-increasing problems, but fortunately Harvard Square is well-served by public transportation, and many Harvard employees are able to utilize commuting options other than driving to get to work.

The most valuable data on the actual behavior of Harvard commuters is found in the Massachusetts Department of Environmental Protection mandated *Rideshare Reports.* Based on randomly distributed questionnaires, these reports give a break down of the commuters at Harvard, the nature of their commute, incentive programs in place to reduce the number of single occupancy commuting vehicles and the projected effects of such programs. Data from the 1999 report is illustrated below and demonstrates the salient truth that less than a third of Harvard commuters drive alone to work! The demand strategy is commitment to reduce this fraction.



A large percentage of Harvard Commuters do not drive alone to work
(1999 Rideshare Report)

2.1 Managing Demand – The CommuterChoice Program

Given the burgeoning demand for parking in Cambridge, a strategy for managing the demand becomes both important and necessary. Harvard has taken some steps towards addressing this issue with the implementation of the CommuterChoice program. Introduced in January 2000, the program is designed as a collection of incentive initiatives to encourage Harvard employees to use alternative modes of transport other than driving alone in a car.

The program is mandated by the Massachusetts Department of Environmental Protection as a means of addressing the mushrooming commute problem across the State. Components of Harvard's CommuterChoice program include:

- Ridesharing
- Carpools/Vanpools
- Bicycling
- Shuttles
- T-pass subsidies

In the short-term, Harvard's goal for this program is a 2.5% reduction of drive-alone trips by 2002.

2.2 Challenges of transportation demand management at Harvard

Although, the CommuterChoice program is definitely a step in the right direction towards more effective management of parking demand at Harvard, several factors have impeded its effective implementation and there has been a limited response to the program thus far - as of March 2001, there were only 60 registered commuters out of a pool of 13,000 Harvard commuters. Some of these factors are:

- General obstacle of changing societal behavior: For many commuters, parking is entitlement and hence it is difficult to consider alternative forms of transportation.
- Particular Harvard attitudes: In the *Rideshare Report* questionnaires Harvard commuters have indicated a low likelihood for switching to driving alternatives. For instance, only 5% of commuters were “likely” to switch from driving alone to car or van pooling[1] even with added incentives.
- Cost-effectiveness of driving: Comparative studies of the options open to the Harvard commuter reveals that driving and parking at Harvard is comparable in most cases and even cheaper in some instances than alternative forms of commute. Given the increase convenience associated with driving alone, the Harvard commuter is mostly acting rationally, in choosing to drive alone.

2.3 Demand-Side Solutions: Our recommendations

Given the challenges associated with successful implementation of an effective TDM (Transportation Demand Management) program at Harvard, we sought to address some of these factors using engineering and analysis methods. In coming up with our recommendations, we examined many possibilities and assessing them in terms of their applicability to the metrics of Harvard’s transportation situation, cost-effectiveness and more importantly, influence on reducing demand for parking in Cambridge. Among our recommendations are:

- Improvements and modifications to existing CommuterChoice program
- Adjusting parking fees
- Expanded commuter shuttle system
- Robust mathematical model for evaluating the incentives program
- Interactive cost-savings tool for commuters

2.3.1 Adjusting Parking Fees

Parking pricing at Harvard is a very important consideration in developing solutions for managing demand. At present, the parking rate for Harvard pooled lots is significantly less than parking rates in comparable commercial lots in Harvard Square (by more than 50%) as shown in the table below.

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[1] Harvard’s *2000 Rideshare Report*

LOCATION	COST OF PARKING
Harvard Pooled Lots (Cambridge)	**$450/year**
Harvard Square Commercial Lots	**$2500/year**
Alewife (Red Line T stop)	**$1000/year**
Harvard Medical School	**$1500/year**

Several other features are unique to the parking pricing structure at Harvard. For instance, the fees paid by the parkers at Harvard only account for the operational costs of parking and do not include the value of land, capital costs and the depreciation of facilities. This policy factors into the comparatively low rates for parking at Harvard.

2.3.1.1 Parking pricing and Transportation Demand Management programs

Cost is among the most influential factors affecting the choice of commuting options. In general, the price of parking is inversely related to the number of drive-alone trips such that an increase in parking fees leads to a decrease in the number of drive-alone trips.

Several studies provide detailed reviews of parking price elasticity[2]. These studies indicate that the elasticity of parking is typically in the –0.1 to –0.3 range (10% increase in parking rates leads to a 1-3% decrease in drive-alone trips) with significant variation depending on demographic, geographic, travel choice and trip characteristics. Thus, if combined with good alternatives, increased prices can induce significant reductions in vehicle trips.

2.3.1.2 Parking fees and planned construction

One of the long-term solutions that is being explored by Harvard as a viable solution to the parking and transportation problem is the construction of underground parking lots. These will serve to simultaneously provide additional parking lots while allowing for green space or construction of new buildings above the parking lots. However, the implementation of this strategy comes with significant cost estimated at $60,000 per space.

The construction of these new underground lots implies an increase in both capital costs and the operational costs of maintaining these garages. Thus given Harvard’s policy of determining parking fees according to operational costs, there will likely be an increase in the parking fees. The increase in parking fees at Harvard Medical School to $1500 with the construction of underground parking lots under the Medical school quadrangle sets precedent for this action.

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[2] Source: http://www.vtpi.org/tdm/tdm11.htm

2.3.2 Expanded Commuter Shuttle System

Another long-term strategy that is being considered as a solution to the parking problem at Harvard's Cambridge campus is the implementation of remote or off-site parking at Harvard-owned sites in Allston and Watertown. Off-set with the increases in parking fees in Cambridge due to construction of underground parking lots, a considerable financial incentive can be applied to make remote parking a more attractive option for commuters. For instance, if the parking fees are upped to the $1500/year level applied at Harvard medical school, the fees at remote parking lots can be maintained at current levels of $450/year. This form of differential parking provides a strong financial incentive for the use of remote parking and helps to foster an equitable demand management program in providing options for commuters whom are lower on the pay scale.

However, for remote parking to work efficiently, there is a need for an effective shuttle system to transport commuters regularly from the parking locations to their places of work in Cambridge. In its current state, the Harvard shuttle system is incapable of implementing remote-parking options effectively.

2.3.2.1 Current State of Harvard's Commuter Shuttle Service

With its heavy focus on routes between the various student houses and class venues, the shuttle is not well adapted for commuter use. Surveys[3] of shuttle riders using the commuter shuttle from the Soldier's Field parking lot at Harvard Business School to Harvard Square, indicate that only a small percentage of 2,428 people who ride the shuttle daily are commuters. On average, we found that there are 5 commuters per trip, riding the shuttle from the 650-car parking lot at the Business school to Harvard square. In addition, the shuttle schedule is infrequent and its convoluted route often makes the commute longer and inconvenient for commuters who wish to take advantage of it.

2.3.2.2 Enhancing Commuter Shuttle Service

In addition to its importance for remote parking, an expanded shuttle system can also help to reduce demand for Cambridge parking in the short term. From data[4] obtained on Harvard commuters and their home and parking locations, at least 600 commuters residing on the Boston/Allston side of the Charles River, park in Cambridge. With an expanded shuttle system, parking at the business school lots will be a more attractive option for these commuters as they can avoid the long back-ups frequently encountered in crossing the bridge at peak commute times. In other words, it will provide a significant congestion reduction benefit.

To address some of the limitations of the current shuttle service for commuters, we recommend a dedicated shuttle buses for direct transportation of commuters every 7.5 minutes at peak commute times. Some specific travel impacts of this recommendation include a reduction in travel times,

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[3] The class rode the shuttle continuously for 2 days to collect data on the timing and usage of the shuttle especially during the peak commute times in the morning and evening

[4] ArcView mapping software was used to approximate the number of commuters in different locations.

increased convenience for commuters and an overall reduction in demand for parking in Cambridge.

2.3.2.3 Cost analysis for an expanded shuttle program

Cost of Shuttle Service	Cost of Equivalent Underground Parking
$100 000/shuttle **$70,000 (purchase of bus)** **$30, 000 (labor cost for driver)** **Assuming average 4 minute waits at peak commute times and 50% occupancy of shuttles,** **# of commuters = 240** **Total annual cost (assuming procurement of 2 additional shuttles)** **$200, 000**	**$60,000 per space** **For 240 parkers, Total Capital Cost** **$29 Million** **Assuming annual discount rate of 5%,** **Total Annual Cost = $1.4 Million** **Annual Cost Savings from using shuttle** **$1.2 Million**

From the analysis above, it is clear that the enhancement of the shuttle service is a more cost-effective option for managing the parking demand in Cambridge than building underground parking.

2.3.2.4 Impact of Shuttle Service on Reducing Number of Single Occupancy Vehicles

At present, there is no method of evaluating the gains obtained from the incentives offered by the CommuterChoice program. Although we estimate a reduction of single occupancy vehicles (SOVs), there are no means, at the present, to quantify this reduction. Hence, we have developed a mathematical evaluation tool to help with the administrative estimation of the effects of different incentive programs.

2.3.3 Commuter Modeling

In order to determine what incentives to put into place and at what levels to set them, there need to be ways of evaluating the effectiveness of those incentives, as well as how new incentives affect the levels that should be set for existing ones. To that end, we have developed a simple model that can be used to quantify the effects of changing incentive levels on the number of commuters who drive and who take alternate forms of transportation. The equations model how people decide between various means of commuting, given their individual situations. Our preliminary model includes only the three most common means of commuting: driving alone (**d**), taking public transit (**p**), and walking (**w**). However, the model is flexible and allows for expansion to include all types of transportation.

This model assumes linear relationships between inputs and outputs which means that, for example, the farther someone lives from campus, the less likely he or she is to walk. In this way, the model is simply an extension of our intuition, but it quantifies the predicted effects so that different incentives can be evaluated for their cost effectiveness.

A quick illustration of how the model works.

The main structure of the model lies within what we call "likelihood functions." The "likelihood functions" are un-scaled, linear relations of our input parameters. Parameters can include anything thought to influence commuter decision on travel methods. Test parameters we used include: distance to campus ($\mathbf{D_c}$), distance to transit, ($\mathbf{D_t}$) and T-pass subsidy ($\mathbf{S}$). These parameters are placed together into a "likelihood function", $l_\mathbf{x}$ (where **x** = **p**, **w**, and **d**), where each parameter influences the likelihood function linearly. Each "likelihood function" is then scaled by a normalizing factor, $f_\mathbf{x}$. We define the "normalized likelihood function" to be the probability that a commuter takes a certain form of transportation, given that he or she can take that form of transportation. The "normalized likelihood", therefore, is set equal to the respective conditional probability – *viz.*

$$\mathbf{P_{w|cw}} = f_\mathrm{w}\, l_\mathrm{w}$$

where $\mathbf{P_{w|cw}}$ is the probability that one walks given that one can walk. . Initially, it is the normalizing factor that is unknown. Combining this definition with the definition for $\mathbf{P_w}$, the percentage who walk:

$$\mathbf{P_w} = \mathbf{P_{cw}} - \mathbf{P_{d|cw}} - \mathbf{P_{p|cw}}$$

our model begins to take shape. Using Bayes Rule for conditional probabilities – *viz.*

$$\mathbf{P_{w|cw}} = \mathbf{P_{cw|w}}\, \mathbf{P_w}/\mathbf{P_{cw}}$$

we can rearrange our definitions into one large equation in terms of "normalized likelihoods" and estimated values.

$$\mathbf{P_w} = \left\{ \left[\frac{\left(f_\mathrm{w}\, l_\mathrm{w}\right)^2}{f_\mathrm{w}\, l_\mathrm{w} - 1} \right] \left[-\mathbf{P_{cd}} \left(f_\mathrm{d}\, l_\mathrm{d}\right) \mathbf{P_{cw|d}} - \mathbf{P_{cp}} \left(f_\mathrm{p}\, l_\mathrm{p}\right) \mathbf{P_{cw|p}} \right] \right\}^{1/2}$$

This above is a new definition for the percentage of people who do, or will, walk. We can see it involves the "normalized likelihood functions" for each of the modes of transportation, as well as four other probabilities. These probabilities can be estimated from current geographical information. For example, we can estimate the number of people who can take public transit, $\mathbf{P_{cp}}$, to be the number of commuters within 3/4 of a mile of transit and live more than 1 mile from where they work, divided by the total number of commuters. We can then use that number to help us calculate the conditional probability that a commuter can walk, given that he takes public transit, $\mathbf{P_{cw|p}}$.

Before we make any adjustments, we must still calculate the values for the normalizing factors, which are the original unknowns. We can rearrange each equation, solving through for individual normalizing factors. Current and previous *Ridesharing Reports* provide these initial conditions. From those reports we define $\boldsymbol{n}_{\mathbf{d}}$, $\boldsymbol{n}_{\mathbf{p}}$ and, $\boldsymbol{n}_{\mathbf{w}}$ to be number of people driving, using public transport and walking respectively.

For our simplified model, let $\mathbf{P_p}$, $\mathbf{P_w}$, and $\mathbf{P_d}$ be defined as percentages taking transit, walking and driving, respectively. We obtain these initial values in terms of the 1999 *Ridesharing Report* data as: $\mathbf{P_x} = \boldsymbol{n}_{\mathbf{x}} / \boldsymbol{n}_{\mathbf{total}}$ (for **x** = **p**, **w**, **d**). This is the value we plug in to find the normalizing factors.

$$\boldsymbol{f}_{\mathrm{w}} = \frac{\mathbf{P_w} - \left[\mathbf{P_w}^2 + 4\mathbf{P_d}\,\mathbf{P_{cw|d}} + 4\mathbf{P_p}\,\mathbf{P_{cw|p}}\right]^{1/2}}{-2\,\boldsymbol{l}_{\mathbf{w}}\,\mathbf{P_d}\,\mathbf{P_{cw|d}}\,\mathbf{P_w}^{-1} - 2\,\boldsymbol{l}_{\mathbf{w}}\,\mathbf{P_p}\,\mathbf{P_{cw|p}}\,\mathbf{P_w}^{-1}}$$

Here, the walking normalizing factor has become a function of all known values. We then lock the normalizing factor at this value, and move on to getting some real value out of the model.

Now that the model is set up, and the normalizing factors are set, the input parameters can be modified, with small perturbations, and the output is the predicted change in the distribution of commuters who drive alone, take the T, and walk. In our demonstration, we included the T-pass subsidy, an already-existing incentive, so that we can match the model's predictions to known data by inputting input parameters as they exist in reality.

The model can be expanded in future to include other types of incentives such as input parameters so that their effectiveness can be evaluated. Also, other types of commuting, such as carpooling and bicycling can be added to make the model more complete.

As an example, we increased the T-pass subsidy from its current level of 40% to 50% and the model predicts that there would be a modest but significant increase in the number of people who would take mass transit.

Now, while the model is useful for evaluating the effectiveness of incentives prior to taking an extensive survey or implementing changes in incentive programs, it is ultimately up to the individual commuters to choose to take advantage of them. Different incentives will apply to commuters in different situations, and commuters may often just continue what they are doing because they are not aware of the benefits they could receive from taking an alternate form of transportation.

2.3.4 The Web

As we all know, the World Wide Web can be a useful medium to make information more accessible to people. Our SimLot program (see Section 3.3.4 and Appendix 3) has a web-based front end so that it can perform its calculations on the DEAS server but be accessible to users of any platform, from anywhere, with an easy-to-use graphical interface. For the demand side of the parking issue, the web provides a way to reach commuters, not only to inform them of incentive programs but also as a tool to enhance convenience and flexibility. We propose two web tools that will help commuters analyze the benefits of incentive programs and make carpooling more attractive.

2.3.4.1 Cost analysis web tool

While it is of course important to be able to evaluate the effectiveness of incentives using models and surveys, the true test of an incentive program comes after implementation. It is ultimately up to the individual commuters to choose to take advantage of available incentives. Commuters need to be aware of incentive programs in place, and they need to be convinced that changing their commuting habits could allow them to receive significant benefits. Changing levels of incentives will cause different incentives to appeal to each commuter. A case study will illustrate this and motivate the discussion for a web tool to help commuters analyze the benefits of incentives in place. This analysis will focus on the economic costs associated with each means of transportation. There are of course other considerations that influence an individual's decision, most importantly time and convenience. However, cost is a very important factor, and a large enough economic incentive can overcome resistance to taking alternative means of transportation.

This case study will focus on a typical commuter, Jones, who works 250 days in a year. He currently drives 4.5 miles from his home to campus, where he parks in the DEAS lot, a permit for which costs him $450 per year. As an alternative to driving, he could drive 1 mile to Alewife station, where he could park and take the Red Line subway to Harvard station. Parking there costs $4 per day, and the cost of a monthly subway pass is $35, but Harvard offers him a 40% discount under the current incentive system. Finally, he lives half a mile from the T bus stop, and the bus would take him from there straight into Harvard Square. The cost of a monthly bus pass is $25. The Internal Revenue Service allows a deduction of 32.5 cents per mile when using a car for business purposes, so the cost analysis will use this figure, as it includes all costs associated with using a car, including the prices of gasoline, insurance, and depreciation. The yearly costs for Jones are thus as follows:

Driving alone	**Taking the T**	**Taking the bus**
Permit$450	**T passes $252**	**Bus passes $180**
Car expenses $731	**Car expenses $163**	
	Alewife parking $1000	
Total $1181	**Total $1415**	**Total $180**

Taking the bus would be cheapest for Jones, but he may consider that option not to be viable as it is the slowest alternative; also, for many others, taking the bus would involve a longer walk or multiple transfers. However, since a considerable number of commuters living within a few miles of campus do live on or near bus lines, it may be a viable alternative for many people. Currently, driving alone is cheaper for Jones than commuting by subway. Note that the Alewife option is similar to an offsite-parking situation in that the commuter drives to a large offsite lot and is then transported to campus by a frequent-service form of mass transit.

However, it is probable that the fee for a parking permit will increase significantly in the near future to offset the cost of building an underground parking garage. Parking at the Harvard Medical School costs $1500 after the parking was placed underground there. If the parking permit for Jones were only to double to $900 yearly, it would cost him $1681 per year to drive alone, more than taking the subway would cost him. Though the $250 or so that he would save is significant, it may not be enough for him to abandon the convenience of having a car near his office. This difference, however, can be increased when taking into account the other incentives that are being proposed. For example, increased parking fees as disincentives to park, cheaper Harvard-managed offsite parking, and increased T pass subsidies will all make it even more attractive for Jones to take the subway. At some dollar amount Jones may decide that the time saved or convenience gained by driving alone is not worth the extra money that he has to pay.

Other commuters may in the same way reconsider driving alone if they are presented with an analysis such as this with the conclusion that they could be saving several hundred or a thousand dollars. To inform and aid commuters about incentives available to them, we propose implementing a web-based tool that would allow them to perform this same sort of analysis on their own situations. The web form will ask for some basic information, such as how far the user lives from campus, as well as questions relating to incentives with value judgments attached, such as "Parking in Allston will save you $800 per year, and there is a free shuttle every 7 minutes between the lot and the Cambridge campus. Would you consider parking in Allston?" This web application would then add up the costs based on the responses to the questions and present the user with a basic analysis. The form is available as a demonstration on the course website.

2.3.4.2 Carpool-matching website

According to the 1999 and 2000 *Rideshare Reports*, carpooling and vanpooling are means of commuting that are not widely used on campus, though this alternative has the potential to make a significant difference in reducing the number of single-occupancy trips to campus. Carpooling has its own set of additional considerations, such as insurance and the need to depend on other people who may not always be reliable. It also lacks the convenience and flexibility that driving alone and even taking the subway offer. However, in addition to being promoted with economic incentives, carpooling can be made more convenient and flexible through the use of information technology.

To that end, we propose implementing a web-based automated carpool matching system. Commuters will sign up with the system with their information, such as address and schedule. Since the process is automated, the system can create and adjust carpooling groups whenever more people sign up or when people leave the system. Participants can be notified by email or by telephone automatically. Additional flexibility will be provided by an instant matching facility where a commuter can log onto the website and request a different carpool to join on a one-time basis in case his schedule for the day is different from a regular day.

The implementation of this website is beyond the time and human resource scope of this course, but a demonstration of the facilities described is on the course website. The proposed finished product would be driven by an SQL database to hold personal and group information and a map database, such as MapQuest, to locate people's homes.

3 PARKING ACCESS CONTROL

Encouraging people to commute by some method other than driving alone is only one piece of a possible solution. The other involves an increase in the efficiency of a use of the current parking supply. As mentioned earlier, 1 in 7 parkers in our test lot was found to be illegally parked. Access control, or limiting entry to lots, is one way to eliminate such invalid parkers.

Current parking enforcement measures do not effectively deter illegal parkers from parking in Harvard-operated lots, resulting in fewer permits issued and less convenience for legal parkers. We tackled the task of maximizing existing parking lot efficiency through access control technologies. The DEAS/Littauer parking lot served as our test lot; from it, we collected lot flow and lot count data and determined that on average one in seven vehicles are parked illegally. We researched various access control solutions, such as license plate readers, proximity cards, swipe cards, and radio frequency identification (RFID). By developing simulations to model traffic flow through an access control gate, we concluded that an RFID system would be the best solution to implement. Finally, we worked with contractors to form an RFID access control model for the DEAS/Littauer lot.

3.1 The Enforcement Problem

On Harvard's Cambridge campus, parking attendants currently provide access control at the Everett Street garage, Broadway garage, and the 38 Oxford Street lot. While manning a booth from 8am to 5pm, an attendant makes sure that each incoming vehicle has a valid permit tag. While this is an effective way to prevent illegal parkers from entering Harvard-operated parking lots, placing an attendant at every lot on Harvard's Cambridge campus is not a feasible solution to deter illegal parkers. Harvard, presently, cannot justify setting aside additional space required for booths and money for employing dozens of new parking attendants.

Most of Harvard's parking lots, including the DEAS/Littauer parking lot, do not have any form of access control. We took two full days of lot count data in one-hour increments from our test lot (see Appendix 2).

Members of the Engineering Sciences 96 class patrolled the lot jotting down how many vehicles had valid tags and the number of vehicles that had invalid or no tags. While we realized that a few vehicles may have been valid, but lacked a visible permit tag, we found that the majority of illegally parked vehicles were clearly not supposed to be in the lot (*e.g.* cars with NITE, HBS, 38OX, QUAD permits, large contractor trucks working on Cruft Laboratory construction, and cars of Harvard Law School students). We found that on average one in seven vehicles were parked illegally. The largest percentages of illegally parked vehicles to total vehicles came between the hours of 9:30am and 12:00pm, which mirrors time of peak traffic flow.

At the lots that lack access control, the only form of deterrence for illegal parkers is a parking ticket. During the weekdays, three Parking Office employees walk the beat writing parking tickets for illegally parked vehicles. An additional person patrols Harvard's lots in a car. Each monitor carries a Radix Rx1 mobile handheld computer, which prints parking tickets, stores lot counts, and links to a Parking Office database of parker profiles, called PowerPark. PowerPark maintains profiles of all valid parkers at Harvard's Allston and Cambridge campuses and a list of vehicles with owners who have no affiliation with Harvard, but have received a parking ticket in the past.

Non-Harvard affiliates are significant contributors to Harvard's parking problem. Last year, the Parking Office issued 33,251 tickets for a variety of violations. Most often, people obtained citations for lacking a Harvard permit (22,328), for parking during unauthorized hours (3,785), or for having an invalid permit (2,613). In 2000, 48% of the tickets issued were written for vehicles in which the Parking Office did not know the owner's identity (see Appendix 8). An additional 23% of the tickets were given to prior Harvard affiliates. In 1999, the Parking Office wrote 28,588 parking tickets, and the most common violation was lacking a Harvard parking permit (19,633). Parking citations rose from 1999 to 2000, and they continued to rise through 2001. In January of this year, the Parking Office wrote 3,526 citations – an average of 114 citations per day. Yet, the percentage of people paying for the tickets continued to drop. From 1999 to 2000, ticket payment for the "no Harvard permit" violation dropped from 39.1% to only 33.7%.

Parking ticket rates have not substantially risen in the past ten years. Under the current system, fines are either $10 or $15 depending on the severity of the violation. If one parks in a handicap space or blocks a parking ramp, fines rise to $25. In contrast, Cambridge parking tickets typically cost $20 and up, perhaps prompting some to park in Harvard-operated lots instead of incurring the heftier Cambridge parking ticket fine. Further, infrequent offenders may know that not paying the Harvard ticket does not normally result in further punishment.

3.2 Access Control Technologies

3.2.1 Our Recommendation

Instead of raising parking ticket rates, we propose an access control system to prevent illegal parkers from ever gaining access to Harvard's parking lots that is both convenient and cost-effective. The system would consist of a barrier gate, an ID tag for each vehicle, a ID tag reader positioned near the barrier gate, and a database of legal parkers.

An access control unit with a barrier gate would provide a number of enhancements to the current parking enforcement provided by the Radix handheld unit. Parking would be more convenient for legal parkers. For example, instead of driving around the DEAS lot only to discover that all spots have been taken, parkers would know whether the parking lot has vacancy before entering it. An LCD display above the barrier gate could toggle between vacancy and no vacancy in order to alert the parker of the lot's status. If the lot has no vacancy, another LCD display would list nearby lots with vacancy where the parker could park.

The Parking Office's pledge to guarantee every valid parker a parking spot in his or her assigned lot would be difficult in any situation given the number of Mobile permits (clearance to park in any Harvard lot). However, the Parking Office could improve the efficiency at which they sell permits. An access control system would provide instantaneous lot counts and lot flow data. From this information, they could easily maximize lot usage by identifying the peak lot count and determining the number of new permits to issue.

As stated earlier, we determined from our survey of the DEAS/Littauer lot that on average one in seven vehicles were parked illegally. Last year, Harvard issued 49 permits for 49 spaces in the Littauer lot and 109 permits for 92 spaces in the DEAS lot, at a rate of 15% over-issued. Therefore, an additional 7 permits in the Littauer lot and 16 permits in the DEAS lot could be issued.

Increased security is an advantage of any access control system. Harvard University's ID card services currently keep two weeks worth of records of who has entered and exited buildings with swipe cards. If a crime occurs in a specific building, Harvard will know who was around at the time of the crime. Likewise, with a parking access control system, the Parking Office will have lot information twenty-four hours a day, seven days a week on who has entered and exited lots in case of building vandalism or car theft.

In the future, the Parking Office may wish to offer tiered parking permits for infrequent users. An access control system could help make sure that those people paying for limited usage actually park on a limited basis. Many access control products on the market can easily incorporate accounting features that deduct from a parking account database, like PowerPark.

With these advantages in mind, we researched a number of access control solutions from companies like Computer Recognition Systems, Sirit, TransCore, Amtech, Eidams, and MAC Systems. We focused our efforts on swipe card and radio frequency identification (RFID) technology.

3.2.2 Swipe card (Magnetic Stripe Cards)

Swipe card (or magnetic stripe card) technology has become ubiquitous in recent years with the prevalence of credit card and ATM applications. At Harvard, the Identification and Data Services Office distributes magnetic stripe cards to all students, faculty, and staff. These ID cards provide a means for the Dining

Services to monitor how many meals a student eats per week, for a student to pay for food and laundry with CrimsonCash, and for all Harvard affiliates to gain door access to Harvard buildings. Cardholders swipe their ID card through a reader, which sends identification information to a variety of databases for processing.

The encryption is complex, but the technology is fairly simple. The magnetic strip on the backside of a swipe card contains binary information, which can be interpreted by a reader. Harvard-issued swipe cards contain three data tracks designated 1, 2, and 3 that hold 550 bits, 200 bits, and 550 bits, respectively. The ID office has only needed to encode track 2, which contains a cardholder's ID number, the card's reissue number, expiration date, and site code. The eight-digit ID number is the most important information on the card as it is the data checked against Harvard's databases. The reissue number becomes important if the card is lost or stolen. In that case, the Identification and Data Services Office programs a new card with a higher reissue number, and the Office cancels the old card's reissue number in its database. Typically, Harvard ID cards have an expiration date of one year after the issue date, unless the card is temporary.

Harvard currently offers swipe card access control to many of its buildings. When a cardholder swipes his or her card through a door reader, it takes the ID number and transmits it to a database for clearance. If the database contains the ID number, a green light will appear on the reader indicating the door has unlocked. However, if the user is not found in the database, permission is denied and a red light appears on the reader.

How would swipe card technology work in terms of access control for parking lots? A parker drives his or her vehicle up to a barrier gate and stops the vehicle next to a swipe card reader. The parker rolls down the driver-side window and swipes a Harvard-issued swipe card through a reader. The ID number on the magnetic stripe is transmitted from the reader to a Parking Office database via an Ethernet connection. If the user's ID number matches an entry in the database, the barrier gate will open.

3.2.3 Radio Frequency Identification (RFID)

Radio Frequency Identification (RFID) is a wireless technology that uses radio signals to transmit ID information. An RFID system consists of a reader and a tag. The reader can send radio signals at either low or high frequencies. Low frequency readers typically provide slower data transfer and have to operate at closer distances to a tag. A high frequency reader (UHF – 900MHz), on the other hand, is particularly well suited for vehicle access control because the read range can easily exceed fifteen feet, and it can send/receive large amounts of data at very fast speeds.

RFID tags come in two flavors: active and passive. An active tag uses a battery to send the identification data contained in the tag. Depending on the tag's use, batteries typically last for five years. Since most active tag batteries cannot be replaced, most users purchase an entirely new RFID tag after the battery has died. Alternatively, a passive tag does not use battery power to send data. Instead, it receives its power from the high frequency signal emitted by the reader. As a result, passive tags have an unlimited lifetime, and a transmission range of only 12 feet. Active tags have a considerably larger read range. Eidams quoted us as their active tags working at up to 60 feet.

RFID is a mature technology. Harvard has installed RFID access control units on thirty doors around campus for handicapped students, faculty, and staff. Users are given passive tags, which they hold up to a one-foot square reader mounted at the handicapped entrances. These passive tags have read ranges of 6 inches. RFID technology is used in the Fast Lane and E-ZPass electronic toll collection system, which has been installed throughout New England. A receiving antenna at the tollbooth reads account information on a tag attached to the windshield of a vehicle. The system electronically deducts the toll from the driver's prepaid toll account. Convenience is a major advantage for the Fast Lane and E-ZPass systems since the driver does not need to stop the vehicle to pay the toll, which reduces gas, emissions, and service time at the tollbooth.

How would RFID technology work in an access control system at Harvard parking lots? First, the reader's antenna, placed 8 feet above the ground, sends a high frequency radio signal (900MHz) towards an incoming vehicle. A tag, positioned on the vehicle's windshield, picks up that signal and returns another signal with 32-64 bit Identification data. It takes only three-tenth of a second for a reader and tag to exchange information. The reader receives the ID number and checks it with an online database, operated by the Parking Office. If the parker has access to the lot, the barricade gate will open.

RFID access control technology has been applied to a number of parking lots around the nation. TransCore has installed Amtech readers for Coca-Cola in Atlanta, Federal Express in Memphis, the LSU Medical Center in New Orleans, the Dallas-Fort Worth Airport, and the World Trade Center in New York City. Locally, Eidams has installed RFID solutions at the U.S. Post Office (25 Dorchester near South Station) and at 2000 Commonwealth. From our correspondence with vendors, these sites have had success maximizing the efficiency of their parking lots and improving the convenience for legal parkers with their new RFID systems.

3.2.4 Cost Analysis

Swipe card and RFID access control solutions have comparable costs. MAC Systems quoted us a price for a swipe card system: The reader with a heater unit and keypad would cost $600; ID cards would not cost anything as they are already issued annually by the Identification and Data Services Office. In contrast, we obtained quotes from Eidams on an RFID system: An RFID interrogator would cost roughly $3500. Passive tags cost between $2 and $18 each, while active tags range from $18 to $60 each. Assuming a price of $30 per active tag for the DEAS/Littauer lot, 181 tags would cost $5,430. One of the major advantages for an RFID system is that it requires no maintenance. Swipe card reader parts, on the other hand, have to be replaced every eighteen months.

The main cost of any access control system will be construction of an island for the readers. MAC Systems estimated that installation costs would be approximately $12,000. Eidams did not offer a definitive number.

Parking rates may have to increase to implement these systems, but the extra revenue generated from the sale of additional permits will pay for most of access control system's cost. Given that rates for next year will be $450 for a permit in our test lot (DEAS/Littauer), the 23 additional permits mentioned earlier would bring in $10,350 per year of extra revenue. Clearly, this extra revenue justifies implementing either a swipe card or RFID access control solution.

3.2.5 Contrasts between Swipe Card and RFID Technologies

We looked in depth into the advantages and disadvantages of incorporating swipe card and RFID technology into an access control solution. The main advantage for a swipe card system is that parkers could use their Harvard-issued swipe card to gain access to a parking lot. The Parking Office would not have to issue new tags; instead, they would only need to maintain a database of ID numbers that correspond to legal parkers. With RFID, the Parking Office would have to issue new tags every three years for active tags. At first, they will need to distribute flyers telling Harvard parkers how to place the RFID tag on the windshield in order to obtain maximum range. Since many Massachusetts residents are already familiar with Fast Lane and E-ZPass, the installation of RFID tags should not prove to be a major obstacle.

The major disadvantage for a swipe card system is the potentially large traffic backups. A parker must stop the vehicle and roll down the window to swipe the card through a reader. Alternatively, an RFID system is hands-free and does not require a line of sight between the tag and the interrogator. RFID tags operate effectively from inside a vehicle and in undesirable conditions with dirt, dust, snow, and rain – which hamper visibility. A swipe card system would have difficulty operating under such conditions, but RFID technology would effectively work under the worst conditions and with shorter service times. Before deciding on either Swipe card or RFID technology, we looked into exactly how long vehicle backups would be with each system.

3.3 Evaluating the Consequences of Access Control Implementation

The implementation of an access control system in a parking lot effectively solves the problem of unwanted vehicles occupying valuable lot space. However, introducing access control technology also poses a new problem: traffic backup. While a standard parking lot allows vehicles to enter and exit in a virtually instantaneous manner, a lot equipped with an access system requires cars to slow down or stop as they enter. Consequently, a line of slowed or stopped cars may form during periods of peak traffic flow. If this line of cars becomes to long, it may spill out of the parking lot and onto neighboring residential streets, essentially creating an additional traffic backup problem.

For this reason, when considering an access control solution for Harvard, it is important to examine how implementing an access control system in the University's parking lots would affect traffic flow in the vicinity of each lot. It is also important to examine whether traffic backups would be so lengthy that lot users would have to wait inordinate amounts of time to gain entrance.

3.3.1 Objectives And Methodology

To investigate these issues, we wanted to model the effect upon traffic flow of adding an access control system to a standard parking lot. An effective model would allow us to evaluate the possibility of traffic backup spilling out of a parking lot and onto neighboring residential streets. Additionally, such a model would allow us to compare the efficiency of different access control technologies, simulating how quickly each technology processes cars on average and in the worst case scenario.

In order to construct such a model, we first needed to collect some data. Specifically, we needed to find out about current traffic patterns and trends, such as when cars typically arrive, and how many cars arrive in total over the course of the day. We also needed to find data on the performance of access control systems.

To process this data, we developed a computer program to simulate traffic flow in and out of a parking lot. This simulation program, called SimLot, considers traffic flow patterns, parking lot characteristics, and the presence of an access control system. Using these input parameters, SimLot calculates traffic backup data over the course of a day, and determines the average and maximum amount of time that any car waited in line before entering the lot.

Analyzing this simulated data would allow us to examine the magnitude of access control-related traffic backup and to evaluate the efficiency of different access control systems.

3.3.2 Traffic Flow Data

We began the process of data collection with a one-day traffic flow study of the DEAS/Littauer parking lot. For the entire time between 8:00am and 6:00pm, an observer positioned near the lot's entrance would record the current time whenever a vehicle entered or exited the lot. To obtain a general understanding of who was using the lot, we also classified each vehicle as a parker, a contractor, or a delivery vehicle. We also took note of single-occupancy vehicles.

After reviewing the traffic flow data that we collected during this initial study (a histogram of which can be found in Appendix 2), we identified the time between 8:00am and 10:00pm as the morning "rush-hour" period of peak activity. Reasoning that this timeframe was the period during which traffic backup into the lot was likely to be maximal, we set up a video camera to monitor the lot entrance during these hours. After videotaping morning rush-hour traffic in the DEAS/Littauer lot for a full work week, we transcribed and averaged the week's rush-hour data and integrated it with our original full-day survey. The net result was an overall data model for traffic flow into the DEAS/Littauer lot.

The chart below (an enlarged version of which can be found in Appendix 3) illustrates this overall data model. The horizontal axis represents the time of day, beginning at 8:00am and ending at 6:00pm, divided into 10-minute intervals. The vertical axis represents the number of vehicles that entered the lot during each 10-minute interval.

As you can see, there is a distinct "morning rush-hour" period of increasing traffic starting at 8:00. The rate of traffic inflow peaks around 9:30 at 16 cars per 10-minute interval, and then generally subsides until

11:00. The remainder of the day consists of peaks and valleys of lesser magnitude, mostly centered around the beginning of each hour.

3.3.3 Access Control System Performance Data

To gather data about the performance of access control systems, we observed the swipe card system presently in use at the Business School's main parking lot and recorded how long it took the system to process each vehicle. We began timing each vehicle when it had stopped in front of the card reader, and we stopped timing after the gate had closed behind the car following its entrance.

In observing the Business School's access system, we noticed that there were two primary types of swipe card users: those who had their cards ready and windows rolled down when they arrived at the gate, and those that didn't. The former group, comprising roughly 4/5 of all users, passed through the access control system in 11 seconds on average, while the latter group averaged 19 seconds. Overall, the average time for all users was 13 seconds.

It should be noted that these observations were conducted on days with ideal spring weather. One can infer that, in the case of typical Cambridge winter weather, the average time for a driver to pass through a swipe card system would presumably be greater. This is because a much greater percentage (if not all) of lot users would wait until they arrived at the gate to roll down their window, and thus the average service time would increase to about 18 seconds, based on our observations.

We also obtained information about the performance of an RFID system from Transcore/AmTech and Eidams. Since an RFID system can respond to a request for access within a few tenths of a second, the system's efficiency is largely determined by how fast the gate can be raised. For this reason, we also obtained performance data for a variety of gate models.

According to TransCore, an RFID system could query and respond to a request for access within 0.1 seconds, while Eidams quoted an RFID response time of 0.3 seconds. TransCore also informed us that a typical access gate can open or shut in about 3 seconds. A faster gate model that can open or shut in about 1 second is also available at a considerably higher price.

3.3.4 Computer Simulation: Simlot

As mentioned earlier, we have developed a computer simulation called SimLot that models traffic flow in and out of a parking lot. This program takes as input:

- traffic flow data that provides a sense of when cars tend to arrive and depart throughout the day
- information about the parking lot, such as the number of entrances/exits and the type of access control system in use
- miscellaneous user-specified options, such as the number of times to repeat a simulation

Given these input parameters, SimLot generates traffic backup data over the course of one day[5], and reports the average and maximum length of time that it took for any one driver to enter the lot. For a more detailed description of SimLot and its modeling capabilities, please see Appendix 3.

In order to simulate traffic backup into a hypothetical DEAS/Littauer with access control, we supplied SimLot with the traffic flow data that we collected from the DEAS/Littauer lot, as well as the access control system performance data that we collected from the Business School, Eidams, and TransCore. We then ran a simulation of the DEAS/Littauer lot with both a swipe card access system and an RFID system, obtaining simulated traffic backup and waiting time data in each case.

3.3.5 Analysis Of Simulated Data

A chart showing the simulated traffic backup data generated by SimLot for both a swipe card access control system and an RFID system in the DEAS/Littauer parking lot can be found in Appendix 2.

From this chart, we can see that the swipe card system generally produces a longer backup than the RFID system, especially during the morning rush hour period. During this peak period, as many as 5 vehicles were waiting in line under the swipe card system, while under the RFID system only 3 vehicles were backed up at most.

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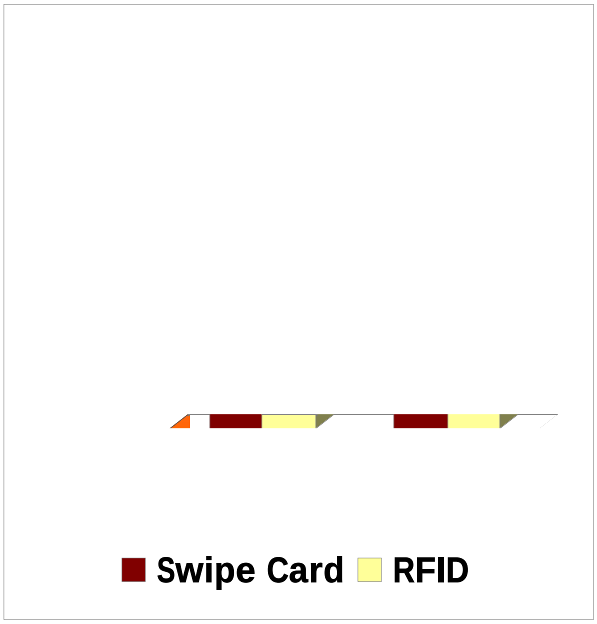
[5] Currently, one "day" in SimLot is defined as 10 simulated hours. If necessary, this definition can be modified rather easily in the SimLot program source code.

Perhaps the more telling figures, however, are the simulated waiting times. The graph below depicts the average and maximum waiting times of the simulated swipe card and RFID systems in the DEAS/Littauer lot. In both the average-case and worst-case scenario, the RFID system significantly outperforms the swipe-card system.



Under the simulated swipe card system, on average a driver entered the lot within 19 seconds of arriving, while the average waiting time under the simulated RFID system was just under 3 seconds. The longest amount of time that any one vehicle waited in line for a swipe card system was 72 seconds, and the longest wait in the RFID simulation was only 10 seconds.

What conclusions can we draw from this simulated data? From the traffic backup data, we can deduce that, if a swipe card access control system were to be implemented in the DEAS/Littauer lot, it would require a driveway of about 5 car-lengths leading from the street to the gate in order to accommodate traffic backup. On the other hand, if the DEAS/Littauer lot featured RFID access control, the driveway would only have to be about 3 car-lengths long.

Additionally, from the waiting time data, we can infer that an RFID access control system in the DEAS/Littauer lot would be (on average) about 6.5 times more efficient than a swipe card system.

3.3.6 Conclusions

Based on this study of traffic flow in the DEAS/Littauer parking lot and simulations of a hypothetical DEAS/Littauer lot featuring swipe card or RFID access control, we have determined that implementing an RFID access control system in this particular parking lot is a sound access control solution. In addition to being more convenient to lot users, an RFID system would process vehicles about 6.5 times as fast as a swipe card system and require a shorter driveway to accommodate traffic backup. With regard to the latter point, one familiar with the DEAS/Littauer lot entrance is aware that a driveway of five car lengths or more is not practical without serious reconstruction due to the proximity of the driveway curb to the neighboring buildings.

Furthermore, one can extrapolate the conclusions of this DEAS/Littauer lot study to similarly structured lots and garages. While pure linear extrapolation will not be extremely precise in dealing with lots that are significantly larger than the DEAS/Littauer complex, it will provide a decent initial approximation in lieu of a full simulation of the lot in question.

For the results of additional simulations we have performed using SimLot, please see Appendix 3.

3.4 Access Control Proposal

Based on the data generated in our tests in SimLot and our desire to avoid inconveniencing users while hoping to improve the current state of parking, we recommend the installation of an access control system based on Radio Frequency Identification (RFID). Controlling use of the majority of parking spaces at Harvard would allow greater use of the current parking infrastructure, allowing more university affiliates to park on campus, thereby providing greater convenience to them and shortening the waiting lists for parking in Cambridge. An RFID-based system would be fast and would therefore not inconvenience users. It would prevent long backups at control points, reducing congestion and avoiding inconveniencing traffic and neighboring residents. Finally, an RFID system would not be particularly difficult to install or operate.

3.4.1 Extent of Proposal and Costs

Currently, the Parking Office is responsible for the operation of 5732 parking spaces in 84 lots in Cambridge and Allston. These lots range in size from 2-space areas to the 945-car Business School Lot. They include surface lots, garages, and on-street parking. It is this set of spaces with which our proposal is concerned.

For this proposal, we chose not to consider lots with ten or fewer spaces. Installing access control at all of these smaller lots would greatly increase the cost of implementing the system while effecting only a minimal increase in the number of spaces controlled by the system. We also omitted on-street parking areas, such as the Eliot Triangle and Mill Street parking, since it would be impractical to implement access control in these areas without closing the streets to traffic. Finally, we are omitting the College Dining Hall Lot on JFK Street. This is an important delivery location, where the concerns of food delivery outweigh those of illegal parking.

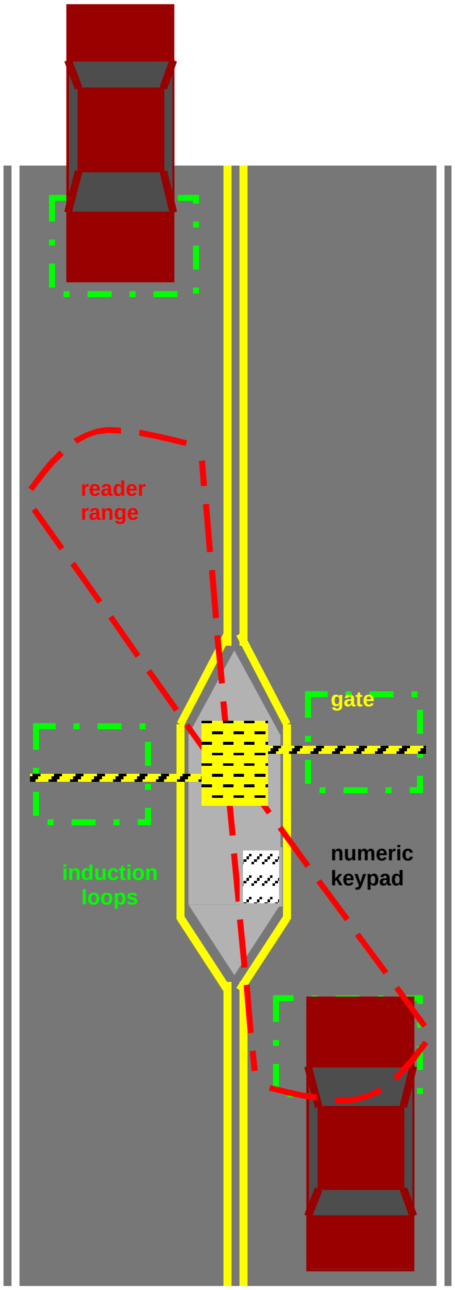
This leaves a total of 5,232 spaces in 48 lots in Cambridge and Allston where we would recommend installation of an RFID access control system. This is over 91% of the total number of spaces under the management of the Parking Office. A map and full listing of these locations is provided in Appendix 1.

MAC Systems quoted us a figure of $12,000 to build an island and install all of the equipment. Eidams gave us an approximate figure of $3500 per RFID reader, depending on the brand of reader used. With two readers per lot (for entering and exiting traffic, as described below), it is reasonable to expect a cost of $20,000 per lot to install an RFID system over these 48 lots. That is a total of $960,000, or $183 per space for 5232 spaces.

3.4.1.1 Malkin Athletic Center

One of these 48 lots deserves a more detailed discussion because of the ramifications of installing access control in it. This is the Malkin Athletic Center lot, between the Malkin Athletic Center (MAC, unaffiliated with MAC Systems) and the MAC Quad. This is an 18-space lot with an entrance on each end: one on Holyoke Street and one on Dunster Street. Because of the layout of the predominantly one-way streets in the area, the most convenient way to drive from Mount Auburn Street to the Eliot Triangle area (Kirkland, Eliot, and Winthrop Houses) involves travelling through the MAC lot from east to west.

An access control system on this lot would prevent its use as a road in this manner. Despite this, we would recommend installation of an access control system here because it is one of the most abused lots on the campus. It is not uncommon to find over half of the cars in this lot illegally parked. We would recommend closing the side of the lot on Dunster Street and installing an access control unit on the Holyoke Place side, which would result in more efficient traffic flow than the alternative of an entrance on Dunster and not on Holyoke. Emergency vehicles needing to get from Mount Auburn to the Eliot Triangle area could travel the wrong way for one block on either Dunster Street or the private university road in front of Winthrop House. Other drivers would have to travel a more circuitous route through Brattle Square. Currently, many of these drivers are parking illegally in the area and would be less likely to be in the area if parking was controlled.



3.4.1.2 DEAS/LITT Model

As described earlier, we studied the Division of Engineering and Applied Sciences (DEAS) and Littauer (LITT) lots in detail, gathering information that was helpful in the preparation of many parts of this report. After studying use patterns and traffic flow into the DEAS/LITT complex, we are able to make a more specific proposal for an access control unit in this lot, which will address some of the issues that we would expect to find at other lots around the campus.

The DEAS/LITT complex has a single entrance on Oxford Street which leads into the DEAS lot. To get to the LITT lot, users must drive through the DEAS lot. It is thus a simple choice to put a single access control unit at this entrance. By doing this, we lose the ability to separate permit holders of the two lots. However, this is not a significant concern. In our surveys of the lots, we found only one instance for part of one day of a DEAS permit holder in the LITT lot, and no instances of LITT users in the DEAS lot.

Based on the SimLot simulation data, which predicts maximum car backups of three cars at peak times, we recommend placement of the access system just to the east of the east edge of Pierce Hall. This leaves more than the required three car-lengths to avoid traffic backup into the street. All equipment would be mounted on an island between the entrance and exit lanes. This equipment would include a gate for each lane, a reader directed into each lane, and a numeric keypad.

Using active RFID tags, which use batteries to increase the range at which they can be read, the readers should be able to query a tag in a car when the front of the car is still 12 feet from the gate. This number will vary depending on the specific brand of RFID tag and reader used, but the result is that cars will be required to do only a rolling stop, which will keep traffic flowing quickly into the lot.

The keypad is a solution for visitors to the lot. Those who plan their visit in advance, for example to visit a professor or a facility, would be able to call into the office and obtain an access code for the lot. By typing this code into the keypad, users without a valid RFID parking pass can still gain access to the lot. Codes can be reassigned to be unique for different users, and they can be activated or deactivated from a central office to increase security for the lots.

Finally, there will be four induction loops buried in the road. Induction loops are essentially car sensors; an automobile on the road surface causes a current to flow through the loop, and this is converted into an electric signal. These loops will aid in traffic flow as well as acting as safety mechanisms. There will be two in each lane: one in advance of the gate, and one directly under the gate.

For a car entering the lot with a valid permit, the process is simple. When the front of the car is 12 feet from the gate, the induction loop, sensing the car, enables the RFID reader. The reader queries the tag on the car, passing the information along to a database that will determine whether the user is a valid permit holder for the lot. All of this happens in less than one second. As the car performs a rolling stop, the gate opens, and the car enters the lot. The gate remains open until after the car has crossed the second induction loop (the one under the gate) or until some amount of time passes. The gate will remain open as long as there is a vehicle over the second induction loop to prevent damage to vehicles.

The exit lane is configured slightly differently. Exiting cars will not need to be verified before they can exit the lot, so there is no need for the gate to remain closed until the RFID tag has been queried. In this case, the induction loop is placed 25 to 30 feet before the gate, and the gate is triggered not by the reader, but by the induction loop. The gate remains open until the vehicle has crossed the second induction loop (beneath the gate). There would still be a reader in the exit lane, but instead of being the trigger for the gate, this reader would merely record traffic, providing information to be used by the Parking Office and providing the lot with an anti-passback feature.

The anti-passback feature is an important attribute of the lot. An access control system is of limited utility if it can be easily circumvented, for example by passing an RFID tag to another vehicle entering the lot. This might be tempting for faculty and staff with guests or family members, or for contractors or other temporary users of the lot who might want to bring in more vehicles than they have been allowed. With a database recording all vehicle traffic, it is possible to prevent passing back of a tag. Once recorded as entering a lot, the tag would not be able to trigger opening of an access gate until after it is recorded leaving the lot. While this is not a foolproof solution to the passback problem, it is an effective deterrent.

3.4.1.3 Parking Office Database

The database controlling the DEAS/LITT complex, was well as all other lots on the access control system, would be maintained by the Parking Office. Currently, the Parking Office uses a software package called PowerPark by T2 Systems to manage permits and citations. The new database could be built as a replacement for the current PowerPark system or as an extension of it; PowerPark can be customized to allow external programs to access and modify its databases.

The database should be linked to the ID Services database to maintain current information on all users. The ID Services database maintains updated information on all university affiliates and shares this information with other administrative databases within the university. Each linked database is given access to the specific information from the ID Services database that is necessary to its operation. The Parking Office would likely obtain billing information and ID numbers from this database. It would supplement this with additional information on registered parkers, including the RFID code in that user’s tag and the lot or lots in which he or she will have permission to park.

3.4.1.4 Access Control and Automated Parking

The need for ID numbers should be explained briefly. While we are proposing an RFID-based access control system, there is one application in which swipe card systems, using the current Harvard ID cards, would be appropriate, and this is in the automated garages described later in this report. In order to retrieve a car, a user must identify himself to a machine. While this can be accomplished by issuing users a ticket each time they park a car, this is less secure, more expensive, and less convenient for users than using a Harvard ID card. Carrying an RFID tag outside of the car would be an even less practical solution. If the database contains ID number information, it can handle swipe cards just as easily as RFID tags, making swipe cards the best solution to retrieval of cars from an automated garage.

3.4.1.5 Benefits to Parking Office

Managing the database will allow the Parking Office to obtain information on lot use patterns and traffic flow for each lot in the system. The information can be broken down by permit type or individual user to allow better management of the lots. A better understanding of lot use patterns would allow the Parking Office to more accurately decide the number of permits to be issued. In this way, the Parking Office could maximize revenues and convenience to its users, by selling permits and reducing waiting list times, while still ensuring that every permit holder has a parking space available when he or she wants to use it.

In addition to restricting permits to certain lots and certain days or times of day, which the Parking Office currently does, a computerized access system would allow other forms of control which would allow the Parking Office to offer new services to its users. One example would be a debit parking system, in which a user would be allowed to park a certain number of times per month, or a certain number of times during a year. Users could pay in advance for a certain number of parking days, and the system would debit their accounts by one day each time they parked. A program of this type could replace the current metered parking lot in the North Yard area. Software to handle this type of program has been developed and deployed by Eidams and other access control installers.

Another service made possible by the use of an automated system with a real-time database is the installation of informational signs for users. As a simple example, "Lot Full" signs could be implemented based on the instantaneous lot count information in the database, saving users time searching for parking spaces in full lots. Signs could also direct users to the next nearest parking lot with available space.

3.4.1.6 Special Cases

The full lot condition is one of a number of special cases that must be considered in implementing an access control system. In this situation, the access control unit should still allow valid users into the lot, proving them with ample space to turn around, but a sign should notify users of the full lot status. The system must also be configured so that a user registered to park at a lot that is full will have access to a nearby lot. In general, if a lot is more than 90% full, users of that lot should have access to other, nearby lots.

Provisions must be made for invalid parkers arriving at an access control gate; there must be space for them to turn around. Many access control systems provide an "escape lane" for unauthorized vehicles, but most of Harvard's parking lots, including the DEAS/LITT complex, do not have enough space around them for such a lane. The solution must be created on a case-by-case basis. For the DEAS/LITT complex, we would propose a widening of the access road in the area in front of Pierce Hall to create a 35-foot parking/turnaround lane. This provides space for unauthorized vehicles to turn around and return to Oxford Street.

This turnaround lane can also be used as temporary parking for visitors who did not call in advance to receive an access number. Visitors could leave their cars here temporarily while visiting the office to obtain an access number. This would require occasional surveillance by the office staff in Pierce Hall to ensure that no one is using the area for long-term parking. Surveillance would be simple, involving only a routine check out the window.

Deliveries are the group of current lot users who would be most affected by the installation of an access control system, especially in the DEAS/LITT complex. Many delivery companies do not arrive use the same vehicles or the same drivers from one visit to the next, so issuing an RFID tag would be impractical. For frequent deliveries with different drivers or vehicles, issuing access numbers would be inconvenient for both the drivers and the office, requiring the office to issue a new number to a new driver for each visit. Issuing a long-term access number would reduce security in the access system, and we would not recommend it.

For deliveries and service personnel who visit the lot regularly, including Harvard University vehicles, issuing an RFID tag is an option. In all other cases, we recommend routing deliveries to central delivery points, reducing traffic through controlled lots. Services and small deliveries could be delivered on foot, and larger items could be distributed by Harvard vehicles.

4 PARKING STRUCTURES AND TECHNOLOGIES

For the purposes of this report, the term "parking structures and technologies" refers to any object, building, or general technology which stores parked cars or facilitates the storage of parked cars. These play an integral role in any solution to parking problems. Obviously, they are necessary to hold the users' vehicles and keep them safe until they are retrieved. In addition, however, these structures and technologies represent the biggest cost and biggest use of space for most parking facilities. The choice of parking structure or technology used for a particular facility plays a critical role in how much that facility will cost, how it will integrate with its surroundings, how easy it will be to use, and a number of other important factors.

This section of the report looks at a number of different types of parking structures and technologies, with a focus on the following ones:

1. Standard Aboveground Garages
2. Standard Underground Garages
3. Valets
4. Stackers
5. Automated Garages

Items 1-4 above will be referred to as "non-automated technologies." For each structure or technology, the report explains what it is, how it works, its advantages and disadvantages, and examples of the structure or technology in use. More space is devoted to automated garages than the others because this technology is the most technically complicated and least common (at least in the US) of the ones listed above.

We used the following goals in our analysis of these different structures and technologies:

- Minimize the cost of both constructing and maintaining parking spaces.
- Reduce the amount of surface space used for parking. Another way of saying this is to

increase the space efficiency of parking.

- Create parking systems that are easy to use and convenient.
- Find solutions that are aesthetically pleasing for the Harvard community and its neighbors.
- We derived these goals from Harvard's own strategic parking goals as they appeared to us through Mr. Vautin's initial presentation and through our discussions with other Harvard administrators. The discussion below for each of the parking structures and technologies is framed around these goals.

4.1 Standard Aboveground Garages

A "standard aboveground garage" refers to an aboveground structure in which cars are parked on multiple floors. The cars travel within the floors and between the floors using their own power. Inter-floor travel occurs using ramps built into the overall structure. Most standard aboveground garages are constructed out of concrete. Many have facades made of other materials (brick, stone, stucco, glass, *etc.*) which allow them to better blend in with their surroundings.

Aboveground garages are the most common type of parking structure in the United States, after regular surface lots. They are used in a variety of settings and for a number of different types of use. Aboveground garages are most common in urban areas, such as Cambridge and Boston, where a large number of cars have to be parked in a very limited space. A large number of Harvard parkers use aboveground garages currently on campus.

4.1.1 Advantages of Standard Aboveground Garages

The main advantage of aboveground garages is that they are more space efficient than surface lots. The reason for this is stated in the introduction above: cars in an aboveground garage are parked on multiple floors, so a given surface footprint can provide a parking area many times larger than the area of this footprint. Of course, not all of the floor space in an aboveground garage can be used for parking. Some of this space has to be used for ramps, elevators and stairways for the users, and pillars to support the structure. However, the amount of space left for parking is usually sufficiently large to allow for a great increase in space efficiency over surface lots.

Another advantage of these aboveground garages is that they are easy to use and are very familiar to most users. Since most American drivers routinely use parking garages, no special training or adjustment is necessary for users. Because of this, the garages are very flexible in their use. They can be used for faculty and staff during the day and then for special events at certain times of the year without any worries about how users will respond to such structures.

4.1.2 Disadvantages of Standard Aboveground Garages

One of the main disadvantages of aboveground garages is that they are usually not aesthetically pleasing. It is hard to build large, hulking garages that do not clash with the small, brick buildings that compose most of Cambridge. Since neighbors who are very sensitive to issues of aesthetics surround Harvard, it seems unlikely that Harvard could get away with building a large aboveground garage in the near future, especially on the periphery of its campus.

Another major problem with aboveground garages is that they use up precious surface space. Even though they are more space efficient than ordinary surface lots, they still require a large footprint to park a significant number of vehicles. This attribute is inconsistent with Harvard's goal to devote its limited surface space to non-parking uses.

Aboveground garages are relatively expensive. As shown in the examples section below, new garages cost in the area of $20,000 a space. This is cheaper than standard underground garages, but more expensive than a number of other technologies.

Another disadvantage of aboveground garages is that they can be frustrating to use if a large number of people all try to enter or leave them at the same time. This type of event could cause large backups inside the garage, and delay users for minutes or even hours as they try to find a space or get back out onto city streets. The extent to which this is a problem depends on the particular type of design used. One design used in many of Harvard's existing garages, and planned for Harvard's future garages, is called "park-on-ramp". This design increases the space efficiency of the garage, as it involves parking cars on the ramps that connect the floors. Therefore, the amount of floor space actually used for parking is increased.

The problem with this design, however, is that it requires users to drive by a large number of spaces to get into or out of the garage. A user driving in the garage, then, is forced to wait if a user ahead of him takes time to enter or leave a space. If a large number of people are entering or leaving at the same time, users could have a hard time navigating through the garage to find a space or to leave. Long lines could form inside the garage, causing increased user frustration and large amounts of excess exhaust as cars sit idle.

Finally, the various areas of these aboveground garages often look similar. Therefore, users can be easily disoriented when they come back to retrieve their vehicles, and can be forced to spend time searching for their vehicles. When this is added to the time required to enter the garage and take an elevator or stairs to the appropriate floor, the total retrieval time can be quite large. This is more of a problem in larger garages than smaller ones.

4.1.3 Case Study: MIT's Albany Street Garage

As discussed above, aboveground garages are probably not a practical solution for Harvard's Cambridge campus. We can, however, look at an example of using these garages to solve campus parking problems.

MIT is currently constructing a 1,500 car garage at the periphery of its campus on Albany St. This garage will cost a total of $29 million, or about $19,000 a space.[6] This type of structure is a viable solution for MIT, but not Harvard, because railroad tracks and industrial buildings surround the former, whereas historic residential areas border the latter.

4.2 Standard Underground Garages

Standard underground garages are aboveground garages constructed beneath the surface. Like aboveground garages, they are usually formed out of concrete, and consist of multiple floors linked by ramps. Because they are underground, these garages need extensive ventilation systems to remove the carbon monoxide and other toxic pollutants released by users' vehicles.

Standard underground garages offer an alternative to aboveground garages, and avoid some of the biggest problems with the latter—poor aesthetics and use of valuable surface space. For these reasons, Harvard has turned to underground garages as the main part of its future parking plans. As stated in the introduction to this report, Harvard plans on putting several thousand spaces into underground garages so that surface space now used for parking can be made into new academic buildings and green space. As discussed below, however, this policy involves tremendous tradeoffs.

4.2.1 Advantages of Standard Underground Garages

Standard underground garages have all of the advantages of aboveground garages with even greater space efficiency. By placing parking underground, the surface is now free for new buildings and green space. Some parts of the underground garage, however, do take up surface space—the driveways and ramps which allow vehicles to travel into the garage, the stairways and elevators for people, and the ventilation shafts which exchange air in the interior of the garage with fresh surface air. These items, however, take up very little space compared to a standard aboveground garage. Often, these components can be well hidden so that the presence of the garage is not obvious.

4.2.2 Disadvantages of Standard Underground Garages

Standard underground garages have all of the disadvantages of aboveground garages except for the problems of poor aesthetics and use of surface space. These problems, however, are replaced by another problem—very high cost. As shown in the examples section below, underground garages can cost in excess of $60,000 per space. Most of this cost comes from excavation and foundation work.

There are a number of factors which make excavation work so expensive:

- Soil disposal is very expensive, especially since much of the surface soil on urban sites is considered "contaminated" and has to be trucked to special disposal sites.

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[6] More information about this garage can be found on the following web site: http://www.ellenzweig.aa.psiweb.com/html/infra/alb.html

- Deep pits require extensive support structures to keep the sides from collapsing and to not disrupt the foundations of nearby buildings. These structures include sheeting and slurry walls.
- Most deep excavations go below the water table. The hole has to constantly be “de-watered” with various pumping systems.

For these and other reasons, excavation costs increase faster than linearly with volume. Of the three dimensions for such an excavation, depth is the most significant in terms of cost. Narrow deep holes are much more expansive to make than wide, shallow holes, even if both are the same volume.

4.2.3 Case Study: North Precinct Garage

We can examine some specific numbers for standard underground garages by looking at a garage which Harvard is considering building in the North Precinct area. This garage is planned for the northern edge of the Harvard campus, where two surface lots now reside— the Engineering Sciences Laboratory Lot and the 38 Oxford Street Lot. Harvard is considering replacing these lots and others in the area with this garage so that more space will be free on the surface for new academic buildings.

Our group obtained information on Harvard’s plans from officials at Harvard Planning and Real Estate. The garage is planned to have a total of 675 spaces on 4 levels (dimensions: 190’ x 360’ x 60’ including a 14’ basement for the surface buildings). The garage will have a 450 sq. foot exhaust shaft as well as a two-lane ramp exposed on the surface for 102’. The base cost is estimated to be $40 million, or about $60,000 a space. A cost breakdown for this project is discussed later in this report. A large fraction of this cost is for excavation and foundation work. This garage will be an extremely expensive project, and shows the costs involved with putting large amounts of parking underground.

4.3 Integrated Parking Technologies

A number of simple technologies can be integrated with standard garages and surface lots to increase their space efficiency and decrease the cost of new spaces. Many of these technologies are cost effective, quick to setup, and easy to dismantle. However, these advantages often involve significant tradeoffs which can make these technologies hard to use or risky for users’ vehicles. Two of these technologies, valets and stackers, are discussed below.

4.3.1 Valets

The term “valet parking” refers to a system in which special attendants, valets, both park and retrieve users’ vehicles. In most systems, a user gives his keys and his car to an attendant and then leaves. This attendant parks the car in a garage or lot, sometimes remote from the user’s location, and stores the user’s keys. When the user wants his car back, the attendant goes into the garage or lot, and drives the car back to the user’s location.

Valets can be used for special events or for day-to-day employee parking. Harvard uses valets for some special events at the Fogg Art Museum to park vehicles in the Broadway Garage. Several large corporations, such as EMC in Hopkinton, Massachusetts, have used valet parking as a way to handle rapidly expanding workforces whose numbers exceed the number of parking spaces close to their workplaces. Valet parking offers users' a comforting and personal parking experience. However, as detailed below, it is usually not the optimum permanent solution for parking problems.

4.3.1.1 Advantages of Valets

The main advantage of a valet system is that it increases the number of vehicles that can be parked in a particular lot or garage. The reason for this is that with valets, garages and lots no longer have to have wide aisles and ample maneuvering space for each individual vehicle. Since valets keep users' keys, they can double-park or triple-park cars, and then move them around if necessary.

As opposed to constructing a garage, starting up a valet system requires few, if any, infrastructure changes or new construction. In addition, since the valets are just people, they can be quickly and easily reassigned to other tasks when the valet system is no longer necessary.

Finally, valet systems are psychologically comforting for their users. As the Harvard Parking Office reiterated to our group again and again, people feel most comfortable dealing with other people rather than impersonal structures or machines. It feels very luxurious to have someone else park and retrieve one's car, as opposed to wasting time each morning to wander through a dark, hulking garage in search of an empty space.

4.3.1.2 Disadvantages of Valets

The main problem with valets is that a large number of personnel are necessary to have good service at peak times. Depending on the configuration of the lot or garage, and the distance between the users and their cars, there is a certain finite limit to how many cars a valet can park or retrieve in a given time. If a large number of people converge on the garage or lot at the same time to pick up their cars, a large number of valets will be necessary to handle these people. If the number of valets is too low, or if an unexpectedly high number of people come to park or retrieve their cars at the same time, long wait times are possible. This could greatly frustrate users.

Another problem involved with valets is that the parking is done by people, and as such is open to human error. Cars in valet lots are usually parked very closely together and valets are often under an enormous amount of pressure to park and retrieve cars as quickly as possible. According to John Nolan, Harvard's Director of Transportation Services, who oversaw a large valet garage prior to coming to Harvard, scratched cars and lost keys are inevitable in any kind of valet system.[7] Although these kind of mistakes are covered by insurance, users can get very upset by them.

A good example of how valets can be used to solve parking problems comes from Harvard's plans to

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[7] Interview with John Nolan, Harvard Director of Transportation Services. March 26, 2001.

put valets into the Everett Street Garage. This measure is being proposed as a way to temporarily alleviate parking pressure when the Engineering Sciences Laboratory and 38 Oxford Street Lots are removed for the construction of a new underground garage on that site. In addition, putting valets in the garage will prevent Harvard from "losing" spaces from its total number in the period between the destruction of surface lots and the opening of new underground garages.

Adding valets to this garage will increase the number of vehicles that can be parked from 375 to 488, a difference of 113 cars.[8] The system will cost about $250,000 a year, however. Most of this cost is for personnel; it is estimated that Harvard will need 1 valet on each of the garage's 6 levels, and possibly a separate supervisor as well. While this seems like a large number of staff, it is likely that people will still have to wait if several users all converge on one floor at one time.

4.3.2 Stackers

Stackers are devices that lift vehicles above the normal driving surface so that other vehicles can park underneath them. They can be used in surface lots, aboveground garages, and underground garages. Most systems consist of a piston and cylinder powered with a hydraulic pump. The movement of this piston moves chains or ropes which are attached to a horizontal metal platform. The user drives his car onto this platform, and then the system raises that platform to free up space underneath the vehicle. Once the platform has been elevated, another car can drive and park underneath it. The effect is that cars are stacked one on top of another, and two cars are effectively parked in each physical space.

4.3.2.1 Advantages of Stackers

The biggest advantage of stackers is that they greatly increase the space efficiency of a garage or lot. As stated above, they allow two vehicles to be parked in every space, as opposed to one per space in a non-stacker equipped parking facility. In a facility in which space is very tight, stackers, at least in theory, allow for double the number of cars to be parked.

In addition, stackers are not prohibitively expensive. Prices can be as low as $3,000 per stacker, although most high quality devices used in large facilities cost around $7,000 a stacker (including installation).[9] This is not nearly as expensive as the cost of additional spaces in an underground or aboveground garage. Maintenance costs are also reasonable. Local regulations require that the chains in each stacker be replaced every 10 years. This, however, costs only a fraction of the total cost of the device (around $1,000 per stacker).[10]

Stackers can also be removed or replaced if necessary, since they are not permanently attached to the garage or lot in which they are placed. Once they have been removed, the stackers can be sold on the

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[8] Nolan interview.

[9] Nolan interview; Interview with Tomas Leslie, Harvard Medical School Parking Manager. April 18, 2001.

[10] Leslie interview.

open market, helping to recover some of their cost.

4.3.2.2 Disadvantages of Stackers

One of the main problems with stackers is that they require higher clearance than is usually available in most garages. Therefore, garages must be specially constructed with high ceilings if they are to be equipped with stackers. These higher ceilings greatly increase the actual cost paid for the stacker system. The actual amount this costs per stacker depends on a number of factors related to construction conditions and the garage layout. One estimate given to us by John Nolan was that these higher ceilings could increase the cost per space by $7,000, thus making the total effective stacker cost around $14,000 per device, if we compare it to a standard garage with lower ceilings, the same number of physical spaces, and no stackers.[11] This cost is still less than the cost of new spaces in a garage, but is significantly more than the cost of the devices alone.

Another problem is that only specially trained attendants can raise or lower the stackers. This is because most stackers do not have safety systems to prevent their operators from hitting an elevated car against the ceiling or from crushing a car (or person) underneath the platform. This means that a large number of attendants are required to handle peak periods, when a large number of the stackers have to be either elevated or lowered. Furthermore, these attendants are necessary to move cars— if a person whose car is elevated needs to leave, but another car is still parked beneath that one, an attendant has to drive the non-elevated car to another space.

Because of the way in which stackers are constructed, with poles on both sides of a narrow platform, users have to adjust the way they drive into and out of the stackers. Whereas users can pull into spaces in most lots and garages simply by turning into them, most stackers have to be approached head-on by the user’s vehicle. If the user does not do this correctly, he could break off a mirror or drive a wheel off of the platform, which could lead to extensive car damage. If the user forgets to lower his radio or cell phone antenna, it could be chopped off by the ceiling or the stacker parking platform. Users have to change their driving habits to use most stackers, which can lead to frustration and resistance. These new habits often require more time to enter or leave a space, which means that long backups inside the garage are possible if traffic is great enough.

4.3.2.3 Case Study: Harvard Medical School Garage

Harvard Medical School has a large, underground stacker-equipped garage that provides a good example of the plusses and minuses of using stackers to solve parking problems. This garage sits underneath the Medical School Quadrangle, a grassy, rectangular piece of land in the middle of the Medical School campus. Cars access the garage by driving down a ramp and then going though a tunnel which goes underneath a building.

The garage itself has a total capacity of 508 cars on 2 levels. Most of these vehicles are parked in

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[11] Nolan interview.

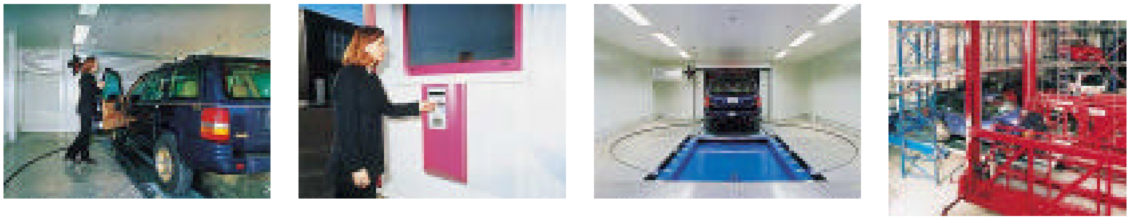
stackers. Users park and retrieve their vehicles themselves, unless they are elevated, in which case an attendant has to lower the stacker. If a user parks underneath a raised car, he leaves his key in a special lockbox attached to the stacker so that an attendant can move his car, if necessary. According to Mr. Leslie, the manager of the Harvard Medical School parking system, new users get used to the stackers eventually, but sometimes break mirrors or antennas as part of the adjustment process.[12]

Another problem with this garage in particular is that 40% of new vehicles sold in the United States cannot fit into the stackers. Since fewer than 5% of the spaces in the garage do not have stackers, many vans and SUVs have to be double parked along the aisles. If current users tell Mr. Leslie that they are buying an oversized vehicle, he tells them that they will have to find somewhere else to park. Since waiting lists for parking areas at the Medical school are more than 3 years long, this acts as a strong inducement for people to keep buying small vehicles. On the other hand, it limits their freedom of choice when buying a new vehicle.

4.4 Automated Parking

4.4.1 Concept overview

Automated or robotic parking is a system whereby a given vehicle is deposited by a user and moved mechanically to a separate storage area where it is retained until retrieved. There are four basic steps involved in the generalized automated parking process: 1) the parker leaves his or her vehicle in a designated area (often called a *transfer room* or *access port*); 2) he or she activates the system with some sort of personal keycard or pay system; 3) the vehicle is then removed automatically; and 4) the vehicle is "parked" in a separate storage area until retrieved.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(Images from www.rondoparking.com)

One of the better introductions to automated parking technology is a March 1994 article entitled "Automated Parking: No Dents, No Bumps, No Tipping," which came out of the annual conference of the International Society of Facilities Executives (ISFE) held in Cambridge, Massachusetts. Copies of this review of a robotic system in Barcelona, Spain are available upon request.

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[12] Leslie interview.

4.4.2 Background and history

Driven by high land costs and soaring urban car populations, European and American companies began exploring automated parking in the first half of the 20th century. The first mechanical parking facility, completed in Cincinnati in 1932, employed a vehicular elevator between 24 floors to store roughly 400 cars.[13] While the first garages were only semi-automatic and required manual operation, those introduced by the end of the 1950s were the first fully automated systems. Many of these suffered from problems related to the hydraulics and pneumatics used for internal transport of the parked vehicles. The reduced cost-effectiveness resulting from these technical complications led to the discontinuation of most of the North American facilities. However, some of these pioneering systems have survived: for example, New York City still has two "classic" garages in operation;[14] the oldest from this generation of early automation that is still in service today was constructed in Bremen, Germany in 1958.

Japan is largely responsible for the modernization of automated parking systems. Again the viability of the technology came directly from high land costs in cities coupled with excessive demand for parking. During the 1980s and 90s industry standards were first advanced. Microelectronics was incorporated into the control components, drawing on automation developed in automobile manufacturing and warehouse conveyance.

Today there are over 5000 automated garages operating in Europe, Asia and Australia. Millions of Japanese park in these systems on a daily basis. In Seoul, Korea—which is home to the world's largest automated garage, built in 1987 with an 849-car capacity—there are more automated than conventional parking garages.[15] There are now numerous well-established manufacturers, such as Nissei Build Kogyo Co., Ltd. of Japan, which has installed over 1000 automated parking towers in Japan, China, Korea, Taiwan, Thailand and Singapore.[16] Automated Parking Systems, a subsidiary of COSS Systemtechnik Gmbh Aalen in Germany has built over 5,500 parking spaces in 200 fully automated structures. Today automated parking is a mature technology that has proven itself over the last two decades.

4.4.3 Types of automated parking technologies

During our study of automated parking, we found a wide variety of available garage types. While conventional parking garages are often formulated individually from architectural standards, similar to buildings, automated parking facilities are machines and are marketed as such. Most manufacturers have several sample systems from which a client can choose; these generic models are then modified for specific

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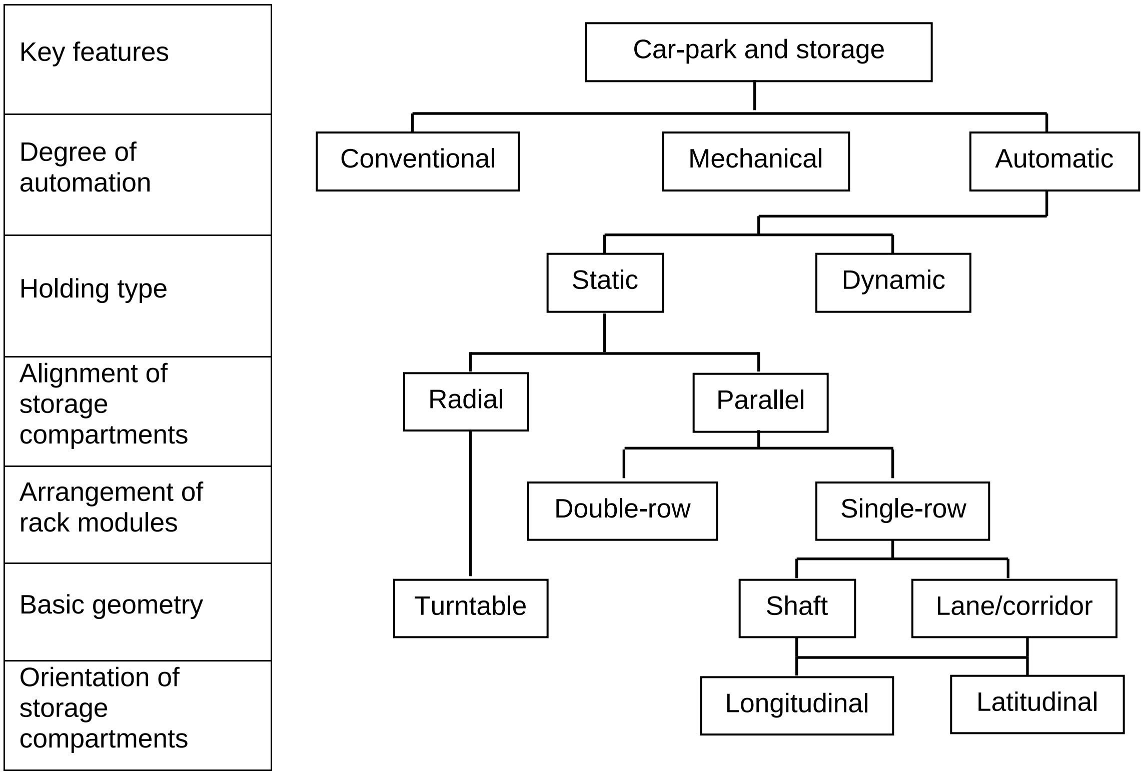
[13] http://www.roboticparking.com/spotlight.html

[14] Ibid.

[15] Gerhard Haag, "The Robotic Parking Experience," Intelligent Transport Systems (2000).

[16] http://www.irel.com.sg/carpark.html

projects. Below is a tree illustrating the main types of car-park and storage systems, focusing on the branch of automated systems.[17]



Explanation

Degree of automation: indicates the level of human activity required to complete the parking process. Conventional refers to typical ramp-style garages; mechanical describes those which include vehicular elevators, lifts or related machinery for the transport of cars internal to the facility.

Holding type: describes the movement of the physical containers in which the vehicles are stored. Static storage embraces all systems in which the car storage compartments do not move. The class of dynamic systems is less fully developed, but involves storage components that have at least one-degree of motion (planned within the garage context).

Alignment of storage compartments: designates the global, directional organization of vehicle storage. In parallel systems the storage modules are arranged along rectilinear coordinates, while radial systems are grouped around a common center (radial systems always incorporate a central turntable).

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[17] Based on the similar “Figure 4” compiled by Dr. Siegfried Wirth of the Chemnitz University of Technology as part of his “Appraisal of system approaches, commercial application and planning of the APS car-park routing and storage system by COSS Systemtecknik GmbH Aalen” (pg. 7).

Arrangement of rack modules: denotes the depth of storage racks, in number of vehicles, measured from the interior access space. The term double-row is similar to double-parking in that there are two adjacent rows of stored vehicles (i.e. any car parked in front of a second car would have to first be removed before the second one could be retrieved). Single-row systems do not need as sophisticated control programming, and tend to be faster, since steps are eliminated. However, they cannot achieve the same parking density as double-row systems.

Basic geometry: explains how vehicles are transported to and from their assigned storage compartments. Turntables that allow vehicles to be turned to face any direction, as well as to be moved up and down between levels, are always found in radial systems. Shaft systems are mainly tower structures (above or below ground), in which the vehicles are transported to storage compartments by means of a central, vertical space. Lane systems instead have an extended corridor in between two storage racks; vehicles are transported along this middle lane, and usually have the added distinction of separate machines for vertical (elevators) and horizontal movement (shuttles) to further distinguishes this class of automated parking from shaft systems.

Orientation of storage compartments: indicates the directional placement of vehicles in their individual storage compartments. Longitudinal storage occurs when vehicles are parked by being inserted into their storage compartment facing either forwards or backwards, *i.e.*, when their longer (horizontal) axis is parallel to the in/out movement. Latitudinal storage is rather when the vehicles are introduced into a storage space with their longer axis perpendicular to the in/out movement.

4.4.4 Radial versus parallel alignment of storage compartments

In our prototype garages detailed later, we proposed only systems with parallel alignment of storage compartments. There are several important considerations that went into this decision. First, because radial systems organize cars in a circular pattern, fewer cars can be stored per level (generally not more than 28) than with parallel systems. This means that radial systems require greater depth than parallel systems to store the same number of cars. With underground garages this reduces cost savings significantly, since the expense of excavation varies more than linearly with depth.

Second, the restriction of radial designs that elevators for transport between levels can only be located in the center creates additional problems. Radial systems cannot accommodate as high a throughput as parallel systems, since the same central elevator must service all vehicles (whereas parallel systems can introduce more elevators for faster operation). Similarly, the overall vehicle capacity of radial systems is limited to a number that can be reasonably serviced by this central elevator shaft (we did not see any designs for radial systems with a capacity higher than 276 spaces).

Thirdly, radial systems are less modular than parallel systems. In order to park vehicles quickly at a fast rate using radial systems, more than one garage would need to be built next to each other. In contrast, parallel systems can be engineered to realize the desired speed within the same unit, and also allow the greater flexibility that each vehicle could be reached by more than one machine. Finally, in the event that a parking system needed to be expanded, this is virtually impossible in the case of an underground radial system—since extra levels of parking would have to be built beneath the existing supply. However, parallel systems can be extended laterally by adding new storage racks along the axis of the access corridor.

4.4.5 Summary of benefits

Automated parking has many benefits when compared to surface lots, conventional parking garages, and the additional parking technologies discussed earlier. Many of these benefits are derived from the modular construction of automated systems. With automation, parking can be abstracted as a cyclical process of storing and retrieving goods (vehicles); in practice, such facilities can be easily customized, concealed, expanded or even relocated.

4.4.5.1 Space Optimization

- Only 40-50 percent volume of conventional garages
- No ramps, passenger elevators or stairs
- Minimal space between parked vehicles
- Modular design allows custom fitting of garage for constraints of site

4.4.5.2 Cost-Effectiveness

- Smaller footprint and volume
- Shorter construction time
- No or reduced internal lighting and ventilation
- No costly concrete repairs
- Lower liability insurance

4.4.5.3 Convenience

- No need to search for parking or remember location of parked vehicle
- Access to parking is localized
- Simple, user-friendly access interface – control software can be integrated with nearly any permit or pay system
- Parking office can monitor garage in real time

4.4.5.4 Environmental protection

- No engines running in garage
- Sophisticated oil-water separation

4.4.5.5 Security

- Theft, vandalism or accidental damage eliminated – since no one enters the area of the garage where vehicles are stored
- Personal safety guaranteed through complete surveillance of transfer rooms

4.4.5.6 Aesthetics

- Any combination of above- or below-ground access and storage possible
- Façade can be tailored to match context
- Modular construction allows entire garage to be moved to meet change requirements

4.4.6 Prototypes for Harvard University

After conducting a preliminary survey of current automated parking technologies, we decided that in order to gauge the possible benefits of an automated parking system on Harvard's campus, we needed to develop specific proposals. Finding the cost of implementing a garage capable of meeting Harvard's needs would allow us to make concrete cost comparisons with conventional garages.

4.4.6.1 Garage 1: DEAS / Littauer (150 cars)

The first garage could serve as a replacement for the parking currently in the DEAS / Littauer surface lot. With this underground garage built under the Law School Quadrangle, Harvard would be able to meet its goal of freeing up surface space for new buildings or green space. We imagined that, with this garage, the Law School Quad could be made into an area more like Harvard Yard—a beautiful, expansive green space that extends up to all of the surrounding buildings, as opposed to a green space lined with an ugly ring of parking.

4.4.6.2 Garage 2: North Precinct (650 cars)

The second garage was proposed to serve as a comparison for the large, conventional garage which Harvard is planning for the site. Because we had preliminary budget estimates and layouts for the proposed conventional garage, obtaining plans for a similarly sized automated garage would allow us to perform a side-by-side evaluation of the two parking technologies for a number of different criteria.

Currently, many of Harvard's smaller buildings have small surface parking lots. Since many existing automated garages are very small (30 spaces or fewer) we also considered proposing a small sized, underground, automated garage. However, in light of our time constraints for this course we decided to focus our attention on the two larger proposals.

4.4.7 Automated parking companies

We initially contacted all the major automated parking companies, outside of Asia, that we were able to find via English-language Internet searching. From their response to our request for more information we were able to gain a better sense of each company and its technology. Based on this and their receptiveness to our preliminary explanation of our objective (developing prototype systems for Harvard University as part of an engineering class project), we chose our short-list of partner companies. These three vendors were APS, CVSS and RoboPark.

4.4.7.1 Proposal Package

We produced a single document to explain the proposals above. This document, which is available to authorized Harvard staff members, introduces Harvard's parking problems and then describes the site and proposed characteristics for each of the two garages. We created a number of other things to accompany this document: a compact-disc filled with digital images, maps, and CAD files of the sites, some printed layouts of the sites with the proposed traffic flows, and a copy of a subsurface soil analysis report for the North Precinct garage site.

4.4.7.2 Transfer of Proposals to Vendors

We sent the package described above to three automated garage vendors:

- Automated Parking Systems (APS)
- Robotic Parking (Robopark)
- Compact Vehicle Storage Systems (CVSS)

We accompanied each package with a cover letter which explained that we wanted each company to tell us how their products could serve the needs explained in the proposals. We specifically asked for the following pieces of information for the solutions proposed by the companies:

- Basic design, including dimensions and how it would fit into the site
- Estimated cost for construction
- Estimated cost for maintenance
- Access time and maximum rate at which cars can be serviced
- Ease of use (for Americans who have never seen such technology)
- Reliability

4.4.7.3 Response of Vendors

The complete proposal responses sent to us are available to authorized Harvard staff members, but are summarized in the following paragraphs. CVSS gave us detailed cost information and layouts for both the DEAS / Littauer and North Precinct garages. Robotic Parking gave us this information for the proposed North Precinct garage alone. APS only gave us some basic information for the North Precinct garage without any layouts or detailed cost figures. More information may come from them after the publication of this report.

The main features of each of these responses are shown in the following tables:

DEAS / Littauer Proposed Garage:

Company	Design	Max. Service Rate	Dimensions	Maximum Capacity	Total Cost (Cost Per Space)
CVSS	Palleted system with central aisle and 2 cranes; 4 transfer rooms reached by a ramp	160 cars / hour	110’ x 97’ x 34’ deep	158 vehicles	$1,660,000 (~$10,506 / space)

North Precinct Proposed Garage:

Company	Design	Max. Service Rate	Dimensions	Maximum Capacity	Total Cost (Cost Per Space)
APS	6 cranes; 12 transfer rooms	360 cars / hour	250’ x 180’ x 35’ deep	624 vehicles	$9,297,600 (~$14,900 / space)
CVSS	palleted system with central aisle and 5 cranes; 14 transfer rooms reached by ramp	630 cars / hour	268’ x 97’ x 40’ deep	661 vehicles	$5,313,000 (~$8,038 / space)
Robotic Parking	palleted system with central aisle and 2 cranes; 6 transfer rooms on surface	480 cars / hour (in only); 400 cars / hour (in and out)	350’ x 100’ x 35’ deep	683 vehicles	$9,448,614 (~$13,834 / space)

The costs above for the CVSS and Robotic Parking designs are primarily for the steel structure of each automated garage, the machinery used to move the vehicles around, and the control systems. They do not include the costs of excavation and the building structure (foundation, walls, and ceiling). Estimates for these non-included costs were obtained from other sources and are shown in the next section of this report.

As explained above, we do not know what is included in the cost figure given by APS since we do not have a detailed cost breakdown from them.

4.5 Comparison of automated and conventional garages

We compared the automated garage proposals we received from vendors to a proposed conventional garage in the North Precinct, evaluating both cost-effectiveness and garage performance.

4.5.1 Construction and installation costs

We compared our proposed automated garages to the large conventional garage planned by Harvard for the North Precinct. This conventional garage, currently being evaluated by Harvard Planning and Real Estate, will accommodate 675 spaces at a cost of about $40 million.

Proposed conventional garage at North Precinct	
Item	Cost
Excavation and disposal	$6,081,545
Foundations (slurry wall)	$5,761,000
Foundations (caisson)	$4,586,400
Concrete	$12,142,789
Other items	$10,792,944
Total	$39,364,678

We estimate that building a garage designed by CVSS with about the same capacity (661 cars) as the proposed conventional North Precinct garage would cost about $18 million, or about $27,000/space. A full breakdown of that cost follows.

Construction and installation costs: CVSS Automated Garage at North Precinct

Item	Cost
Automation[18]	$5,313,000
Machines, electrical parts, controls, access, installation, startup	
Excavation and foundation[19]	
Slurry wall, tiebacks, excavation and disposal, backfill, misc.	$9,000,000
Other construction[20]	
Base Slab (3’ thick) to prevent uplift	$975,000
Waterproofing membrane	$130,000
Roof Slab (1.5’ thick) to support ground loading	$1,425,000
Waterproofing membrane	$142,000
Columns (31)	$62,000
Entrance ramp (slab, walls, excavation and backfill)	$89,000
Dewatering system	$150,000
Fire Protection (standpipe)	$50,000
HVAC and vent – 1st floor	$100,000
Carbon monoxide sensor	$50,000
Construction firm’s overhead and profits	$476,025
Total	$17,962,025

Robotic Parking also submitted a proposal for the North Precinct. Unfortunately, we did not have time to evaluate construction costs for its proposal. However, the proposed Robotic Parking garage is about the

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[18] Formal offer from CVSS. The original offer was in Euros, ¤ 5.969.000, so the dollar cost above will fluctuate with the exchange rate.

[19] Estimate from Mr. Jim Smith, from McCabe Construction. Includes 36’’ slurry wall at perimeter, 5 rows tie backs 54’ deep, backfill and misc., and controlled soils disposal. Used soil data from Harvard Planning and Real Estate.

[20] Estimates from Mr. Alan Wylie, of O’Connell and Sons.

same size as the proposed CVSS garage, so we expect that total construction costs should be about the same.

Robotic Parking gives their price at $9,448,614. This is significantly more expensive than the CVSS proposal. However, that figure includes some construction costs that CVSS does not cover. Most significantly, the base slab of the garage is covered in the above figure, but not in the CVSS proposal. Robotic Parking also makes different assumptions about car size, which may be more appropriate to the United States market. Finally, Robotic Parking used above-ground transfer rooms, while CVSS used underground rooms. Above-ground rooms can be much more expensive.

We also estimated the cost of placing the DEAS/Littauer lot underground, in an automated garage. The costs are as follows.

Construction costs: CVSS proposal for lot in the Law School Quadrangle	
Item	Cost
Automation[21]	$1,660,000
Machines, electrical parts, controls, access, installation, startup	
Excavation and foundation[22]	$3,550,000
Slurry wall, tiebacks, excavation and disposal, backfill, misc.	
Other construction[23]	
Base Slab (4’ thick)	$395,000
Waterproofing membrane	$53,500
Roof Slab (1.5’ thick)	$731,500
Waterproofing membrane	$142,000
Columns (30)	$60,000
Entrance ramp (slab, walls, excavation and backfill)	$114,000
Dewatering system	$75,000
Fire Protection (standpipe)	$30,000
HVAC and vent – 1st floor	$75,000
Carbon monoxide sensor	$50,000
Construction firm’s overhead and profits	$250,350
Total	$7,186,350

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[21] Formal offer from CVSS. The original offer was in Euros, ¤ 5.969.000, so the dollar cost above will fluctuate with the exchange rate.

[22] Estimate from Mr. Jim Smith, from McCabe Construction. Includes 36’’ slurry wall at perimeter, 4 rows tie backs 34.4’ deep, backfill and misc., and controlled soils disposal.

[23] Estimates from Mr. Alan Wylie, of O’Connell and Sons.

4.5.2 Maintenance and operation costs

The Robotic Parking proposal for the North Precinct includes an estimate of maintenance costs. These come to $32/space/month, or $262,272/year for the 683 car garage. In addition, they recommend implementing a $120,000/year reserve fund for future equipment replacements and renovations. Electrical costs for garage operations come to $35,600/year. Harvard's Professor of Mechanical Engineering F. H. Abernathy estimated ventilation costs for the Robotic Parking garage at $19,000/year.

Maintenance and Operation Costs: Robotic Parking Proposal

Item	Annual Cost
Routine maintenance	$262,272
Reserve fund	$120,000
Electrical costs (at $0.10/kWh)	$35,600
Ventilation	$19,000
Total	$436,872

By way of comparison, we estimated the maintenance costs of the proposed conventional garage at the North Precinct at $458,000. Harvard sets aside 2% of the cost of a building each year for short and long-term maintenance. Estimating the cost of the garage at $10 million (the cost of construction after excavation, foundation work, and concrete) gives a yearly cost of about $200,000. To this must be added routine operation costs. The largest of these is ventilation: Professor Abernathy estimated ventilation costs for the North Precinct Garage at $258,000. These figures are both extremely approximate, and depend on many factors specific to the garage.

Maintenance and Operation Costs: Proposed Conventional Garage

Item	Annual Cost
Reserve fund	$200,000
Ventilation and mild warming	$258,000
Total	$458,00

There are three main reasons for the disparity between the ventilation costs of the two garages. One reason is the relative sizes of the garages. The Robotic Parking garage has less than half the volume of the proposed conventional garage, so proportionally less air needs to be pumped through the garage.

Second, in a conventional garage, cars emit exhaust as they drive to their parking spaces. Preventing the buildup of carbon monoxide and other gases requires about 15 air changes every hour. In an automated garage, cars are moved by emission-free electric motors. Also, while drivers need to walk through a conventional garage, only maintenance personnel need to enter the interior of an automated garage. Therefore, an automated garage only requires two air changes an hour. Finally, in winter, air entering the conventional garage would have to be heated slightly, for the comfort of those within—a very high cost. The $258,000 figure above is for very mild warming of the air. If Harvard wished to maintain a constant temperature of 70 F within the garage, the cost would jump to over $2 million/year, and if no conditioning at all is done, ventilation will come to $124,000/year. In contrast, in an automated garage, parkers do not enter the garage and therefore do not require heat.

4.5.3 Garage Performance

We used the CVSS garage in our simulations of garage performance. The machinery in the CVSS garage can handle cars at a rate of 630 cars/hour. This includes 50 seconds for the user to drive into the transfer room and get out of his car (when parking) and 50 seconds for the user to enter his car and exit the room (when leaving the garage).

CVSS claims that the garage it proposed at the North Precinct can park or unpark a maximum of 630 cars/hour. Drivers park their cars in any of 14 “transfer rooms.” CVSS estimates that it will take an average of 80 seconds after a driver has parked before the transfer room is ready to handle another car. This includes 50 seconds for the user to drive into the room, park his car, and leave the area (when entering) or for the user to enter his car and drive out (when leaving).

From the above,

- 1 car/80 seconds for each transfer room = 45 cars/hour for each transfer room
- 45 cars/hour per transfer room * 14 rooms = 630 cars/hour.

Using these assumptions, we used our parking lot simulation program to estimate the delays caused by the machinery. We ran simulations using data on lot inflow and outflow given to us by Harvard Planning and Real Estate for that lot. We also did simulations using the data we gathered for the DEAS/Littauer lot. The differences between the data sets turned out to be unimportant here.

In our simulations, we found that the machinery caused no delays: on most days, all drivers would find at least one of the fourteen transfer rooms available upon entering the lot. On a small fraction of days, a few users during the morning rush would enter the garage to find all the rooms occupied, and those would have to wait for a slot to open up before parking. However, in a 100 day simulation, the longest any user had to wait was about a minute and a half.

We also found that more pessimistic assumptions about the amount of time needed for the average user to complete the parking process did not greatly increase the lengths of the lines faced. Even when we assumed that the average user would take 90 seconds to park their car, rather than the 50 seconds estimated by CVSS, there was never more than 1 person waiting to use any particular slot.

The Robotic Parking garage had a much lower parking rate, of about 480 cars/hour. They said that this could be changed to fit the needs of the lot. We did not have time to find out about the costs of making these changes. We recommend consulting with Robotic Parking for more details. We simulated the Robotic Parking garage, and found that the garage, although it had slower machinery, could handle the expected flow without unreasonable lines forming. Extensive simulation data for both the CVSS garage and the Robotic Parking garage is included in Appendix 3.

In both garages, traffic flow will cause backups in the garage. The problem is not the limitations of the machinery: it is ensuring that all cars can enter and exit the transfer rooms freely without getting in each other's way. When a car is exiting the garage and another car pulls out of a space ahead of it, the driver must wait for the other car to finish pulling out before he can continue. Traffic flow is a problem in conventional garages as well, and can lead to long wait times.

Unfortunately, our lot simulation program is not capable of simulating delays caused by traffic flow problems. We are not certain what is the best way to estimate these delays. There are, however, some factors that may improve the performance of an automated garage versus a conventional one.

First, cars can pull out of access bays in an automated garage more quickly than cars can pull out of parking spaces in conventional garages. Most automated garages rotate cars so that they face outward when the driver picks them up. This means drivers may drive out of the access bay normally, instead of backing out as in a conventional garage. This would reduce traffic flow problems considerably.

Secondly, more space can be built into an automated garage for turning, parking, and passing than for a conventional garage. The Robotic Parking design has above-ground access bays, which allows for a great deal of freedom for cars to move. The more problematic CVSS design does not allow much freedom for cars to pass each other. However, since cars are only driven on the first floor, more space for cars can be added without significantly increasing the cost of the garage.

Finally, the distance that a driver needs to traverse in order to enter or exit the garage is much smaller in an automated garage than in a conventional one. In the CVSS garage, for example, the driver will never need to pass more than 13 slots to get to the exit. In the proposed conventional north precinct garage at, a driver may have to pass several hundred spaces in order to get to the exit.

4.5.4 Summary and conclusions

We believe that automated garages are the best way for Harvard to put parking underground in Cambridge. Harvard has planned to use conventional underground garages to accommodate parking in Cambridge. The main advantage of this approach is that it preserves surface space for construction of academic buildings. Automated garages offer the same advantage, at about half the cost.

We also believe that automated garages will not introduce the new problems faced by other competing technologies. We predict that wait times in automated garages will not be worse than for conventional garages, in contrast to stacker and valet lots. Since most of an automated garage is underground, they do not need to blend with the local architecture. Finally, they are easy to use: damage to vehicles should be much less common than in valet or stacker lots, since there are fewer opportunities for human error.

5 CONCLUSION

After examining the potential benefits of remote parking, we recommend that Harvard should increase the efficiency of its shuttle service. A relatively inexpensive upgrade of one more shuttle would decrease the average wait time. Since most commuters sight inconvenience as a reason to turn down remote parking, we believe that a shorter wait time would make this option more attractive. Combining this service improvement with a new graduated parking rate system will decrease the number of people who park inside of Cambridge. As mentioned, Harvard's current parking fees are significantly cheaper than any commercial fees in the area. An increase in the parking rates would act as a disincentive to park. Rather than simply uniformly raising the fees, however, it would be more effective to offer a scaled rate system. Commuters who take advantage of satellite parking, carpooling, or vanpooling, for example, would be required to pay less than commuters who drive and park alone. We believe that a system of simple commuter tools may drastically decrease the demand for parking spaces. Allowing people to access simple web tools, including a travel cost calculator or a carpool matching website, will educate them that some other forms of transportation may be cheaper, or more convenient than they previously had thought. Our research told us that there would be more involved in a complete solution.

Using the DEAS / Littauer lot as a test example, we determined that one in seven vehicles are illegally parked. The current system of enforcement is not producing the desired result of dissuading people who are not permitted to park in the lots from doing just that. Access control, guarding entry to the lot and permitting only valid users to park, is the best solution to this problem. Access control systems provide better convenience for legal parkers, more control to the Parking Office, and incrase the number of permits sold in each lot. We compared RFID and swipe card, two different access technologies, thoroughly through cost analysis, simulations, and contractor assessments. We recommend installation of an RFID access control system in the majority of the lots operated by the Parking Office, including our test lot.

As the University continues to expand, it will need to maximize parking density, since some of this surface space will be removed. We asked whether introducing appropriate technologies could lead to space and cost savings. Those considered in our comparative study were above- and below-ground conventional garage, valet, stacker and fully automated parking systems. Our analysis suggested that automated parking would be the most efficient solution.

We then developed a prototype for Harvard, in partnership with three independent vendors, to verify that expected savings could be realized locally. Our design proposals demonstrate that implementing an automated parking facility would cut space requirements and overall costs by half. In addition, this system would improve convenience for individual parkers and the level of sophistication of lot management. To enhance Harvard's goal of supporting academic precincts by means of cost-effective underground parking, we recommend the University adopt automated parking systems in place of conventional garages.

For further information, please see our website: **http://www.deas.harvard.edu/courses/es96/spring2001/**

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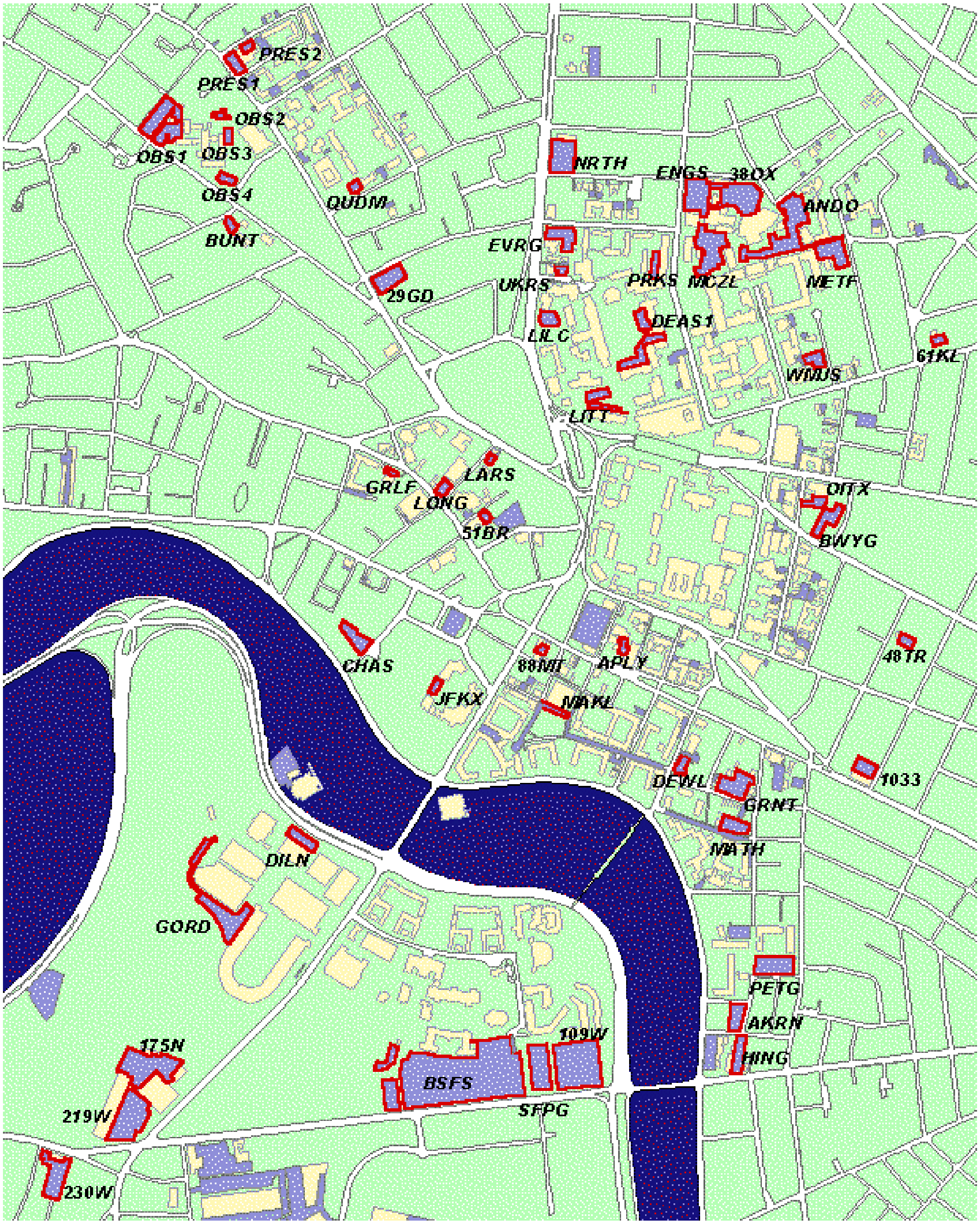
APPENDIX 1: SCOPE OF ACCESS CONTROL PROPOSAL

Map of Cambridge and Allston. Parking facilities are shown in blue; red outlines indicate proposed sites for access control.



Information on 48 proposed sites for access control (outlined in bold, map on previous page).

ID	Lot Name	Spaces	Street Address		City
1033	1033 Massachusetts Ave	83	1033	Massachusetts Avenue	Cambridge
109W	Undergraduate Lot/109 Western	230	109	Western Avenue	Allston
175N	175 North Harvard St	102	175	North Harvard St	Allston
219W	Office Of University Publisher	126	219	Western Avenue	Allston
29GD	29 Garden St	56	29	Garden St	Cambridge
38OX	High Energy Physics Lab (CEAL)	143	38	Oxford St	Cambridge
48TR	48 Trowbridge St	19	48	Trowbridge St	Cambridge
51BR	51 Brattle St	17	51	Brattle St	Cambridge
61KL	61 Kirkland St	17	61	Kirkland St	Cambridge
88MT	88 Mt. Auburn St	11	88	Mount Auburn St	Cambridge
AKRN	Akron St Lot	38		Akron St	Cambridge
ANDO	Andover	199	60	Museum St	Cambridge
APLY	Apley Court	19	65	Mount Auburn St	Cambridge
BSFS	Business School Lot	945		Western Avenue	Allston
BUNT	Bunting Institute	24	38	Concord Avenue	Cambridge
BWYG	Broadway Garage	446	7	Felton St	Cambridge
CHAS	3 University Road I/Charles Square	17	3	University Road	Cambridge
COWP	Cowperthwaite St	48		Cowperthwaite St	Cambridge
DEAS1	Division Of Applied Sciences	93	21	Oxford St	Cambridge
DEWL	Dewolfe St Housing I	80	31	Grant St	Cambridge
DILN	Dillon Field House	42		North Harvard St	Allston
ENGS	Engineering Sciences Lab	109	20	Oxford St	Cambridge
EVRG	Everett St Garage	375	8	Everett St	Cambridge
GRLF	Radcliffe President/Greenleaf Lot	14	76	Brattle St	Cambridge
GRNT	Grant St Lot	77	9	Grant St	Cambridge
HING	Camb Elect - Hingham Street	50	387	Western Avenue	Cambridge
JFKX	Kennedy School	13	1	Eliot St	Cambridge
LARS	Larsen Hall	11	14	Appian Way	Cambridge
LILC	International Legal Studies	25	1557	Massachusetts Avenue	Cambridge
LITT	Littauer	57	1521	Massachusetts Avenue	Cambridge
LONG	Longfellow Hall	21	67	Brattle St	Cambridge
MAKL	Iab / Malkin Athletic Center	18	41	Holyoke St	Cambridge
MATH	Mather Lot	47	7	Cowperthwaite St	Cambridge
MCZL	Museum Of Comparative Zoology	135	26	Oxford St	Cambridge
METF	Meters - Francis Avenue Vanserg	78	25	Francis Avenue	Cambridge
OBS1	Observatory	100	60	Concord Avenue	Cambridge
OBS2	Observatory	16			Cambridge
OBS3	Observatory	19			Cambridge
OBS4	Smithsonian/Observatory Parking	27			Cambridge
OITX	Prescott St	19	94	Prescott St	Cambridge
PETG	Peabody Terrace Garage	339	125	Putnam Avenue	Cambridge
PRES1	Press	24	81	Garden St	Cambridge
PRES2	Press	14			Cambridge
PRKS	Perkins Hall	24	29	Oxford St	Cambridge
QUDM	Radcliffe Quad	14			Cambridge
SFPG	Soldiers Field Park Garage	794	111	Western Avenue	Allston
UKRS	Ukraninian Research Institute	15	1583	Massachusetts Avenue	Cambridge
WMJS	William James Hall	42	33	Kirkland St	Cambridge

APPENDIX 2: TRAFFIC FLOW DATA

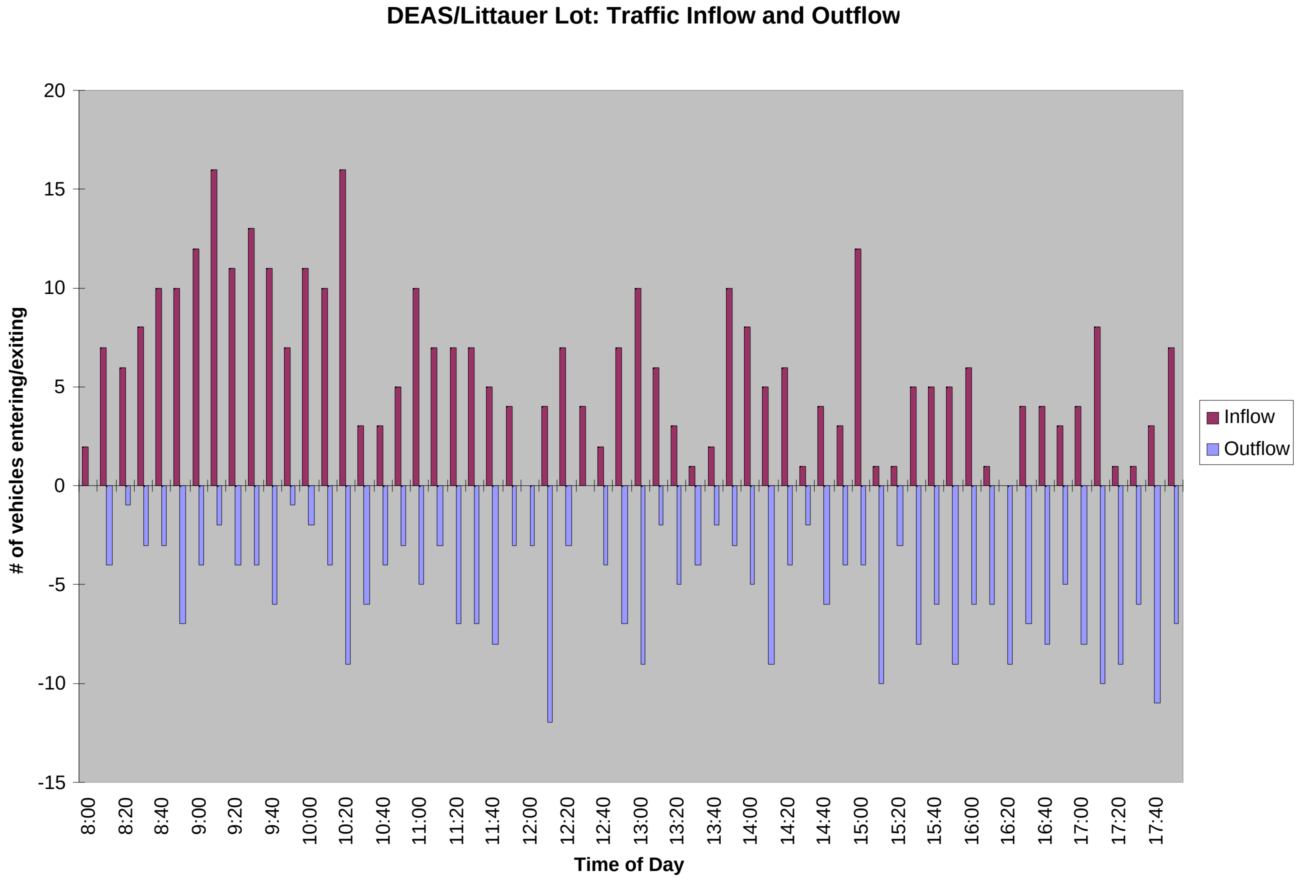
This appendix contains graphical representations of the traffic flow data that we collected during our study of the DEAS/Littauer parking lot. The first section compares traffic inflow and outflow in this lot, and the second section focuses on the inflow data.

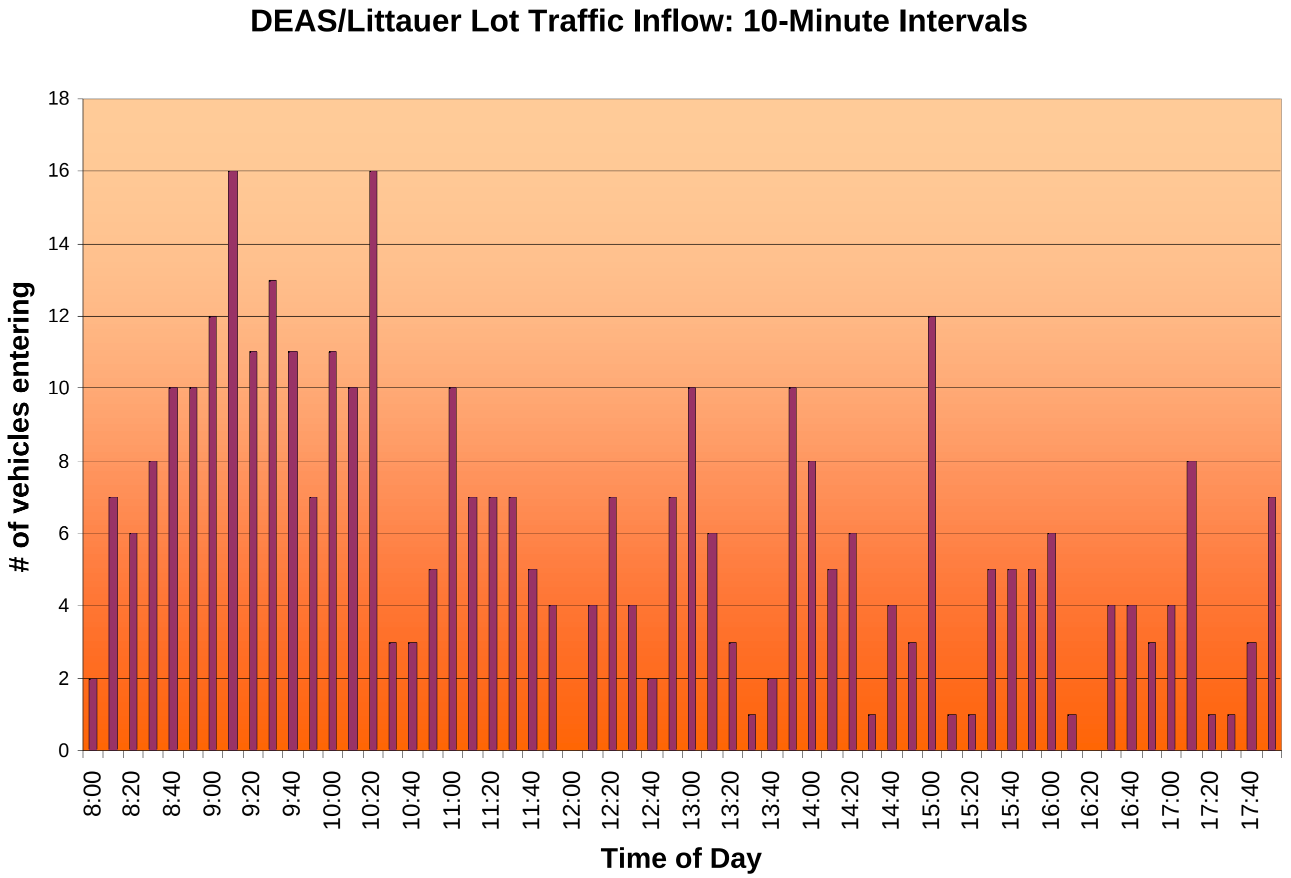
DEAS/Littauer Parking Lot: Traffic Inflow and Outflow

This chart shows traffic flow into and out of the DEAS/Littauer parking lot between 8:00am and 6:00pm according to the data that we gathered (see Section 3.3.2). The horizontal axis represents the time of day, divided into ten-minute intervals, while the vertical axis represents the number of cars entering or exiting the lot during each ten-minute interval.

DEAS/Littauer Lot: Traffic Inflow

This chart shows traffic flow into the DEAS/Littauer parking lot between 8:00am and 6:00pm according to the data that we gathered (see Section 3.3.2). The horizontal axis represents the time of day, divided into ten-minute intervals, while the vertical axis represents the number of cars entering the lot during each ten-minute interval.





DEAS/Littauer Lot Traffic Inflow: 10-Minute Intervals

APPENDIX 3: SIMLOT INFORMATION AND DATA

This appendix contains detailed information about our traffic modeling program, SimLot, as well as simulated data relating to access control systems and automated parking technology. The first section explains how SimLot works, and gives the assumptions on which it is based. The second section gives simulation data for various access control systems, and the third section gives simulation data for automated garages.

Both the SimLot source code and a UNIX executable version of the program will be made available through our website in order to promote future development and extension of the SimLot program. Additionally, we are in the process of constructing a world-wide web interface that will allow visitors to our website to run SimLot simulations. However, due to the complexity of the program, not all of SimLot's features will be available through the web interface. Users who would like to run more advanced simulations are encouraged download the UNIX executable version of the program, or to compile the source code using a UNIX-based C compiler such as GCC.[24]

SimLot Modeling Capabilities and Specifications

This section contains more detailed information about the SimLot program itself, covering its primary algorithm and modeling capabilities. Since the SimLot model is rooted in elementary statistics and queuing theory, some knowledge of these subjects may be helpful in understanding how the program works. Just about any introductory operations research book (such as *Introduction to Operations Research* by Frederick Hillier and Gerald Lieberman) should suffice as an adequate reference.

Modeling Capabilities and an Introduction to Queuing Theory

SimLot is capable of simulating a variety of parking scenarios. We used it to simulate the impact of access control systems on traffic flow and to model delays caused by automated garages.

This is because both access control systems and automated garages are problems in queuing theory. That is, there is a group of "customers" (the drivers) that would like to receive a "service" (parking their car), but the service can only be rendered at a finite rate – for example, six hundred people can't enter a parking lot simultaneously. Therefore, some customers will be forced to wait in line.

This raises the question of how long (on average and at times of peak demand) customers will have to wait in order to receive the service. As one might imagine, a tenured Harvard professor would find the prospect of waiting five minutes to park his or her car every morning to be utterly unacceptable. Additionally, we are concerned with how long the line of customers will be, both on average and at peak times. As

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Brian Schoenbeck (bschoenb@fas.harvard.edu)
W. Douglas Wise (wise@fas.harvard.edu)

discussed in Section 3.2, extensive traffic backups at an access gate may cause traffic to spill onto neighboring residential streets, which the neighboring community would find unacceptable.

Thus SimLot is designed to model a variety of parking-related queuing problems, and can be used both as planning tool (*e.g.,* to consider the effects of implementing access control) and a modeling aide for theoretical situations (*e.g.*, anticipating traffic behavior during Commencement).

Program Input

SimLot considers two different types of input when executing a parking lot simulation: traffic flow data and parking lot parameters. Traffic flow data can be supplied to the program in one of two forms

- An analytical function, such as an algebraic expression, a Poisson curve, or a Gaussian curve. The dependent variable (*i.e.*, x) represents the time of day, while the function value (*i.e.*, f(x)) represents the probability that a car arrives at that time x. Thus f(x) represents the probability distribution of car arrivals over the course of the day, and SimLot uses this probability distribution to randomly determine when individual cars will arrive at the simulated lot.
- A day's worth of traffic flow data, such as the data we collected in our study of the DEAS/Littauer lot (see Section 3.3.2). SimLot will accept flow data in comma-separated value (CSV) format, which can be generated using a spreadsheet program like Microsoft Excel. An example of such a CSV file is:

```
-2,3
-5,6
-3,8
```

Each row in the CSV file represents a five-minute interval. The first value in each row is the number of cars that left the lot during that interval (represented as a negative number), and the second value is the number of cars that entered the lot during the same interval. Thus several hundred of these CSV lines can describe traffic flow into and out of a parking lot for an entire day. Given traffic flow data in this format, SimLot converts it to a probability distribution function in order to randomly determine when cars will arrive at the simulated lot.

Simulation Algorithm

After determining when every car will arrive at the parking lot, SimLot iterates through each second of the simulated day. During each second, SimLot randomly determines whether any cars have arrived during that second, based on the probability function or flow data given as input. If so, for each car that has arrived, SimLot randomly determines the time at which the car will ready to enter the lot. In performing this calculation, SimLot takes in account the rate at which the access control system or automated garage can service one vehicle, as well as how many cars are already waiting in line.

After processing all cars that have arrived in that second, SimLot then checks to see whether a car that is waiting in line has been completely serviced. If so, it removes the car from the line, and takes note of the total amount of time that the car waited in line.

Program Output

After processing all cars that have arrived at all times of the day, SimLot can calculate the average and maximum amount of time it took for any one car to enter the lot. The program can also determine how many cars were waiting in line at every second of the day, and uses this information to determine how long the average line length and average wait was. It also records the maximum amount of time waited by a parker and the longest line of cars that ever occurred during the simulation.

Having completed the simulation, SimLot displays the results of these calculations to the screen. Additionally, the program writes the average and maximum number of cars that were backed up during each minute of the day to a CSV file, which can be easily imported into a spreadsheet program such as Microsoft Excel for graphical analysis.

Simulated Data Relating to Access Control Systems

This section includes simulated traffic backup data that resulted from applying SimLot to the problem of potential traffic backups caused by an access control system. Specifically, this section will discuss the input parameters and results of two simulations of the DEAS/Littauer parking lot. The first simulation modeled a swipe card access system, while the second simulation modeled an RFID system.

Since the only parameters that differed between these two simulations was the type of access control system, the results can be utilized as a comparison between the efficiency of a swipe card system and an RFID system. Please see Section 3.3.4 for the motivation and general overview of this comparative study.

Input Parameters

Both simulations used as input the DEAS/Littauer lot traffic flow data that we collected (see Section 3.3.2), with a total of 355 vehicles entering the lot over the course of the day.

The simulated swipe card access system processed vehicles in an average of 15 seconds total. This figure of 15 seconds was obtained by averaging the average time that it took the “prepared” and “unprepared” Business School lot users to negotiate the access system (see Section 3.3.3). These two groups were assumed to be equally proportionate amongst lot users when taking into account the retarding effects of inclement weather. Additionally, it was assumed that the card reader would fail to properly read the card’s magnetic stripe 5% of the time, requiring the user to swipe their card a second time, and thus adding an additional 3 second delay.

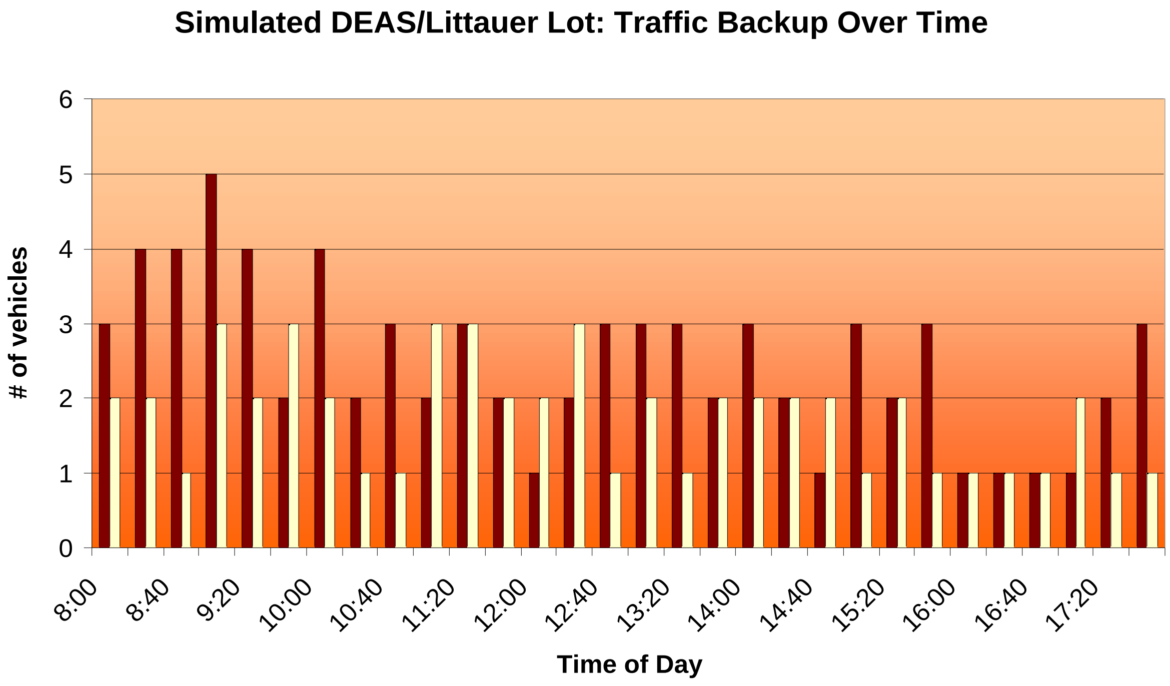
The simulated RFID access system assumed that the RFID reader response time was negligible in comparison to the speed of the access gate, a reasonable assumption given the gate performance data from TransCore (see Section 3.3.3). We also assumed that the RFID reader and gate would be positioned such that the gate would be fully raised by the time the car arrived at it, thus allowing the car to enter without stopping. Assuming that a standard-speed access gate was used, we estimated that the RFID system would effectively process a car in 3 seconds, or roughly the time it takes for the access gate to lower itself after a car has passed through.

Simulation Results

The results of this comparative study were discussed in Section 3.3.5. The following table summarizes the highlights of the two simulations.

	Swipe Card Access System	RFID Access System
Maximum Backup	5 vehicles	3 vehicles
Average Backup	1.11 vehicles per minute	0.163 vehicles per minute
Maximum Waiting Time	72 seconds	10 seconds
Average Waiting Time	19.4 secpnds	2.95 seconds

The chart below depicts the traffic backup data generated by the simulation of the DEAS/Littauer lot with both types access control systems. The horizontal axis represents the time of day from 8:00am to 6:00pm in 20-minute intervals. The vertical axis represents the maximum number of vehicles backed up at the gate during each 20-minute interval. The backup data for a swipe card system is shown in dark red, and the data



for an RFID system is shown in light yellow.

Simulated Data Relating to Automated Garages

The following tables contain simulation data for automated garages under various assumptions.

In the following tables, “average service time” refers to the average amount of time between when a driver enters a transfer room and when the room becomes available for the next user. This is a measure of the speed of the machinery in the garage and how long a user is expected to take to park his car. Typically, this time can be broken down into machine time and user time. The machine time is the time which the garage needs to park the car and prepare the room for the next user. The user time is the amount of time needed for the user to drive into the transfer room, park his car, and leave the area. So

service time = time spent parking + time to prepare room

CVSS gives the machine time at about 30 seconds and the user time as about 50 seconds, for a total time of about 80 seconds. “Average service time” is the independent variable in the simulation. We wanted to see if garage performance remained good if the assumptions made by CVSS regarding user time were too optimistic, so we tried simulations at user times up to 100 seconds. In our simulation, we assumed a standard deviation of 10 seconds in the service times.

“Average wait time” is the amount of time between an individual entering the garage and until his car is parked. It includes:

average wait time = time waiting for a space + average service time

We should reemphasize that this is *not* the amount of time spent waiting for a space to become available. To obtain this value, subtract the average service time from the average wait time.

Maximum wait time is longest time that any user in the simulation waited for a space to become available, added to the amount of time that themselves spent parking. These times usually occurred during the morning rush.

maximum wait time = time spent waiting for a space + time spent parking

Again, this is *not* the amount of time spent waiting for a space to become available. Also, these simulations were done for 100 weekdays, so this refers to the longest time needed for parking by any driver in over three months.

The maximum line length is the most cars in any particular line at any one time, including the car being parked. We assume that each person entering or exiting the garage will go to the transfer room with the shortest line. So the maximum length can only be 2 if at least once during the simulation a driver went to park or retrieve his car and found all the transfer rooms occupied. The maximum length can be 3 if at least once during the simulation, a driver went to park or retrieve his car and found all transfer rooms occupied and with at least one car waiting for them. As you can see, this never happened in the CVSS garage, which has 14 transfer rooms. Again, these simulations were of 100 weekdays, so this refers to the longest line that ever occurred during that period. The longest line on any particular day may be significantly less.

The CVSS garage has fourteen transfer rooms. In this simulation, we used data given to us by HPRE for garage inflow and outflow on a typical weekday. The program each time was run for 100 simulated "days."

Simulation results for the proposed CVSS garage, using HPRE flow data

Average service time(seconds)	Average wait time (seconds)	Maximum wait time (seconds)	Maximum line length (cars)
80	80.01 +- .05	172	2
90	90.01 +- .05	203	2
100	100.02 +- .05	233	2
110	110.05 +- .05	243	2
120	120.20 +- .06	268	2
130	130.35 +- .07	293	2

In this simulation, we used inflow and outflow from our studies of the DEAS/Littauer lot on a weekday for the CVSS garage. Again, the program was run each time for 100 simulated "days."

Simulation Results for the proposed CVSS garage, using DEAS/Littauer flow data

Average service time(seconds)	Average wait time (seconds)	Maximum wait time (seconds)	Maximum line length (cars)
80	80.03 +- .05	167	2
90	89.97 +- .05	206	2
100	100.08 +- .05	220	2
110	110.11 +- .06	244	2

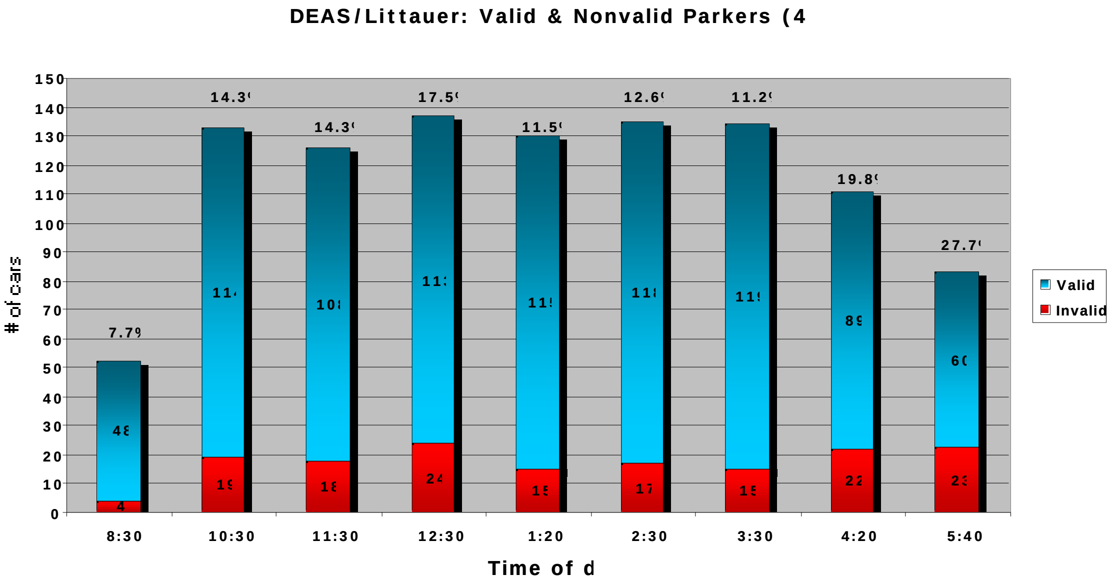
120	120.21 +- .06	274	2
130	130.35 +- .07	299	2

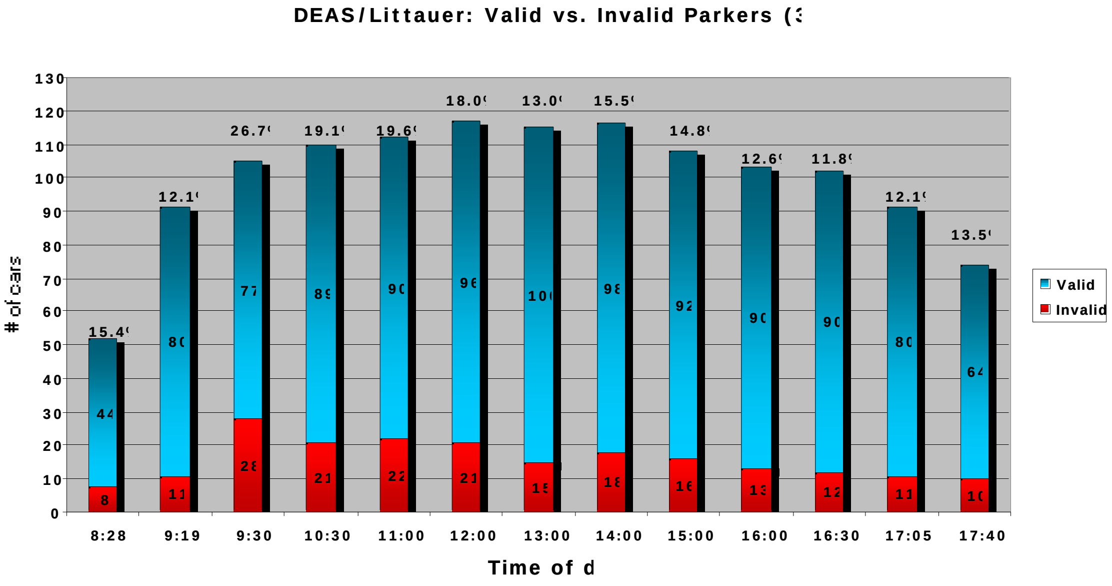
Robotic Parking had a significantly slower garage. Wait times, however, were not unreasonable under their assumptions. Times grew worse under more pessimistic assumptions. Their service data did not include the amount of time they assumed users would take. Robotic Parking estimated service time of 45 seconds/transfer room, with 6 transfer rooms. Flow data comes from Harvard Planning and Real Estate.

Because the Robotic Parking garage has fewer transfer rooms than the CVSS garage, it is more sensitive to changes in their performance.

Simulation Results for the Robotic Parking garage, using HPRE flow data			
Average service time(seconds)	Average wait time (seconds)	Maximum wait time (seconds)	Maximum line length (cars)
45	45.79 +- .07	154	3
50	51.29 +- .08	161	3
55	56.71 +- .09	166	3
60	62.32 +- .10	200	4
65	68.30 +- .12	220	4

APPENDIX 4: LOT USE DATA





APPENDIX 5: CITATIONS BY PARKER TYPE