Methodology Studies in IVHS System Architecture

Kan Chen

Bernard A. Galler

University of Michigan
Ann Arbor

The University of Michigan IVHS

Intelligent Vehicle-Highway Systems
College of Engineering • (313) 764-4332
Professor Kan Chen, 4112 EECS, Ann Arbor, MI 48109-2122, and
University of Michigan Transportation Research Institute • (313) 936-1066
Robert D. Ervin, 2901 Baxter Road, Ann Arbor, MI 48109-2150

IVHS Technical Report 92-05

Methodology Studies in IVHS System Architecture

Kan Chen

Bernard A. Galler

University of Michigan
Ann Arbor

IVHS Technical Report 92-05

Methodology Studies in IVHS System Architecture

Kan Chen

Bernard A. Galler

May, 1992

Abstract

In our search for an appropriate methodology for studying IVHS system architecture, we have concentrated on an attempt to develop a quantitative approach that would be analogous to a recently published quantitative approach to computer architecture. As we examined the fundamental nature of IVHS system design, two characteristics stood out to distinguish it from the design of computers. One characteristic is the concern about multiple attributes. The other is the concern about multiple interest parties. These differences have led us to explore the approach of social decision analysis for IVHS system architecture. A research strategy has been developed accordingly. An initial step of that strategy is to demonstrate the relevance and usefulness of social decision analysis by using it to interpret those IVHS systems that have been successfully implemented, such as electronic toll collection. Initial data collected from such an existing installation in New Orleans have provided preliminary confirmation of our presumptions.

1. Introduction

The central problem in IVHS is to design the overall system involving both the vehicles and the highway infrastructure to perform the principal function of congestion relief in a real traffic environment. However, the problem is so complex that many of the current IVHS field tests are for subsystems that perform lower-level functions, such as nonstop electronic toll collection and dynamic route guidance, all of which are supposed to contribute to congestion relief. Even at these lower levels, the realistic designs have been performed through qualitative judgments, as in other system architecture tasks [Chorafas, 1989], by technical managers whose responsibilities include computers, communications, human interfaces, databases, and networks.

Taking qualitative approaches to IVHS system architecture, innovative engineers generally begin with specific technologies and then perform intuitive tradeoffs in making such system engineering decisions as the relative distribution of intelligence between the vehicle and the highway infrastructure, and the assignment of specific data storage and data processing functions to various computers in the system. For example, in the TravTek system design for route guidance and tourist information by General Motors [Rillings and Lewis, 1991], the assignment of optimum route calculation to the computer on board the vehicle was based on the assumption that American drivers want to have complete control of the optimization criteria; the choice of having four computers (two on the vehicle, one in the traffic management, and one in the TravTek information & services center) was based first on the division of responsibilities among General Motors, Florida Department of Transportation, and the American Automobile Association, and then on the incompatibility of the two map databases carried on the vehicle, one for navigation and the other for route guidance. While this system design is quite understandable for IVHS demonstration purposes, the system design for large-scale implementation begs a more rigorous approach. Moreover, this vehicle-based system architecture is in contrast with the Ali-Scout system developed by Siemens, which assigns route optimization calculations to the computer at the traffic control center. The comparison between competing systems, such as between TravTek and Ali-Scout, has been conducted only on a qualitative basis [Chen, 1992a]. There is a need for a more systematic and more quantitative approach to IVHS system design to help critical decisions made by both users and providers of IVHS.

As we set out to search for a quantitative approach, we had in mind particularly the development of a methodology that would provide a tool for IVHS designers to do cost/performance tradeoffs and that could be illustrated through existing IVHS applications. However, we do not wish to have a methodology that is restricted only to specific current applications, but one that would continue to be useful as IVHS technologies and functionalities evolve in the future. In other words, we would like the methodology to be general enough to withstand the test of time, but specific enough to guide practical decisions. On the other hand, we expect the methodology to be not entirely objective and rigorous, but mostly heuristic (such as using "rules of thumb"), and to accept subjective judgments as a part of the total rationale.

2. Lessons from Computer Architecture

For years, computers have been designed on a qualitative basis analogous to the practice of IVHS design mentioned in the introductory section. Fortunately, a recent book [Hennessy and Patterson, 1990] has been published on a quantitative approach to computer architecture, which appears to have similar goals to those set out by the authors of this report. An intensive effort was thus launched to study that book, with the hope of borrowing ideas therefrom to apply to IVHS architecture.

Some of the general ideas from Hennessy and Patterson's book are obviously useful As it turned out, however, most of the useful ideas are really more qualitative than quantitative. For example, the anticipation of information technology performance to increase rapidly over time would keep the designer from being myopic, so that his design would last through technological changes. The illustration of bottlenecks that restrict total system performance would focus the designer's attention to critical problems and save his energy from being wasted beyond the point of diminishing returns. The analogy in IVHS is to expect decreasing improvement in traffic delays as route guidance systems penetrate the market. Further improvement would call for more radical approaches [Chen, 1992b]. The concept of "locality of reference" in computer architecture refers to frequent (90%) reuse of data and instructions that have been used recently. The analogous situation in IVHS is that link time changes tend to occur in contiguous links due to the same incident — a rule of thumb that would help in assigning the location of link times in computer storage for rapid access.

Another rule of thumb in computer architecture is that optimization of machine design requires familiarity with a very wide range of technologies — compilers, operating systems, logic design, packaging. Analogously, IVHS System architecture optimization requires familiarity with many technologies — traffic modeling, route optimization, RF communications, data communications, *etc.* Given that the three basic aspects of computer design are (1) instruction set architecture, (2) organization, and (3) hardware, one could make the analogous statement that IVHS system architecture also has three basic aspects: (1) communications — boundary between vehicle & infrastructure; (2) organization — data storage and processing hierarchy and location; and (3) hardware — which is the least important aspect for architecture, as in the case of computers.

Some of the rules of thumb in computer architecture are directly applicable to IVHS architecture. This is particularly true in choosing hardware versus software to implement a feature. In both cases, the sole advantage of hardware is performance (such as to accomplish speed in floating-point computation); whereas software has the advantages of lower cost of error correction, easier design, simpler upgrade, and easier handling of complexity. As to overall design, a good approach to both computer architecture and IVHS architecture is to consider a multi-tier approach in which the lowest tier would support some minimum functionalities at lowest cost, below which the system would not be viable. Additional hardware/software and functionalities at the upper tiers should be provided to the users who would evaluate the options by cost/performance analysis.

While there are many analogies and similarities in quantitative approaches to computer and IVHS architectures, we have also identified *two significant differences*. One has to do with the number of attributes for evaluating system performance, and the other has to do with the number of decision makers in choosing the system.

In computer architecture, as described in the book cited above, speed seems to be the single most important attribute in measuring performance. This is in stark contrast to IVHS architecture where many performance measures can be equally important, or of different importance in different situations to different people. In fact, the IVHS AMERICA System Architecture Committee has identified many attributes (with many corresponding performance measures) for the many functionalities of IVHS (as shown in Appendix A). Even for a single function such as route guidance, there are a number of primary performance measures, including total vehicle hours of delay, number of stops, infrastructure cost, in-vehicle unit cost, degree of driver control, and use of frequency spectrum. In addition, there is a number of important secondary performance measures, including safety, ease of use, equity, privacy protection, *etc*. The relative weighting among these attributes will affect the choice of one system versus another. This suggests the need for a multiattribute evaluation criterion for IVHS architecture, and the possibility of applying multiattribute utility techniques [Keeney and Raiffa, 1976] in making design decisions.

Since the computer is essentially a private good for private consumption, a single user or user organization can make the decision about its purchase. This is not the case with IVHS which involves both the vehicle and the highway, and thus involves decisions by both the public and private sectors in its deployment. If either party objects to the system design, it can reject the design, obstruct the deployment, and/or prevent the effective functioning of the system even after its implementation. The potential conflicts exist not just between the private and the public sectors, but also among various organizations within each sector. Not only is there the classical difference between the user optimum for the private driver and the system optimum for the traffic authority, but there are also important issues in multiple jurisdictions among public agencies, and the relationship between IVHS users and non-users.

3. A New Research Strategy

Given the two fundamental differences described above, it appears promising to approach IVHS system design with "social decision analysis" [Chen, 1980; Chen and Underwood, 1988], which integrates quantitatively (1) multiattribute utility functions, (2) Pareto optimum for multiple decision makers, as well as (3) the uncertainties and (4) generalized time discounts considered in conventional system-design decisions. In fact, the social decision analysis approach has been used to demonstrate on paper, in the context of IVHS, the possibility of using economic incentives (thus adding the new attribute of economic gain to the traditional attribute of time delays in traffic optimization) to encourage some drivers to divert from a congested route, thus bringing the user optimum to coincide with the system optimum in traffic assignment [Chen and Ervin, 1990; Halas, 1991]. It appears that a great deal more can be accomplished with the following research strategy, which consists of five progressive stages.

1) Interpretation of successful IVHS applications in terms of social decision making — For example, we can interview major interest parties in several electronic toll collection installations to elicit their respective preference and utility functions. Quantitative analysis can then be conducted to examine the range of Pareto superior and Pareto optimum solutions. The robustness of the solutions (i.e., the relative stability of the win-win solutions with respect to changes of system design parameters) will also be examined.

2) Design of specific IVHS and their field tests based on social decision analysis — For example, we have recently begun to work with the Michigan Department of Transportation and Lockheed Information Management Service Co. to develop an IVHS for trucking operations that will be based on self-financed electronic license plate technology and the previously mentioned concept of using economic incentives to encourage truckers to divert from congested routes [Stafford and Chen, 1992]. Quantitative analysis will be used to guide the collective efforts by the major parties to arrive at an acceptable (and hopefully Pareto optimum) IVHS system design.

3) Quantitative comparison of IVHS system architectures — For example, we plan to develop and apply a quantitative methodology for comparing fundamentally different system architectures for dynamic route guidance, such as the vehicle-based architectures of TravTek and ADVANCE [Boyce *et al.*, 1991] versus beacon-based Ali-Scout [Von Tomkewitsch, 1991]. Since dynamic traffic information is available only intermittently in beacon-based systems, the concept of quantitative value of perfect versus

imperfect information is also applicable here. The comparison will be presented to the providers and selected users (who are all sponsors of the IVHS Program at the University of Michigan) for their critique, based on which the methodology will be refined. In this comparative analysis, we will also look for possible combinations of the two types of systems into a dual-mode architecture that might be superior under certain circumstances.

4) Development and testing quantitative methodology for IVHS system design — For example, we plan to develop, test, and refine a quantitative methodology, based on social decision making, to help design a multi-tier IVHS system architecture [Ristenbatt, 1991]. In the multi-tier system, the choice of IVHS functions to be included in the low-cost tier versus higher-cost tiers will depend on the future and uncertain development of IVHS technologies in terms of both feasibility and cost, as well as on the multiattribute utility functions of the major stakeholders. Thus, all four dimensions of social decision making; *viz.*, (i) uncertainty, (ii) time tradeoffs, (iii) multiple objectives, and (iv) multiple decision makers, will be included to compare alternatives in the multi-tier system design. The challenge here is to use the quantitative analytical approach to stimulate innovative ideas in design.

5) Generalization of the IVHS system design methodology — This will be based on the experience gained after trying out, and improving upon, the methodology developed in all the previous stages. The documentation of the generalized methodology, with specific examples, is intended to be usable for both teaching and professional journal publications.

4. Initial Verification

As a preliminary verification of the new research strategy, we have taken an initial step for its first stage as described in the last section. Specifically, we have tried to demonstrate the relevance and usefulness of social decision analysis by using it to interpret the successful implementation of the electronic toll collection (ETC) at the Crescent City Connection, a bridge across the Mississippi River linking a suburb to the central business district of New Orleans.

It was thought that an important reason for the success of nonstop electronic toll collection is due to the simultaneous gain by the toll collecting agency which can reduce manpower and toll booths, the equipped drivers who can save time by going through the plaza without stopping, and the nonequipped drivers who also save time since the queues are shorter without the equipped vehicles — a truly win-win, or Pareto superior, situation [Chen, 1992a]. The data obtained from the interview as shown in Appendix B indicated that the above conjecture is only partially true. While the bridge toll operator does expect to make enough profit to pass some of it on to the equipped drivers through toll reduction, the nonequipped drivers have not benefited from shorter queues. On reflection, this makes sense because the operator has no incentive to help the nonequipped drivers and would thus close down some booths when the queues for nonequipped vehicles drop below a specified threshold. In fact, by keeping the queues relatively long, the operator puts pressure on the nonequipped drivers to install AVI tags on their vehicles. This is the kind of insight that can be obtained through an interaction between social decision analysis and interactions with major interest parties involved in IVHS.

The above example, with its data and analysis, has provided a preliminary confirmation of our presumptions about the validity and usefulness of social decision analysis for IVHS design. However, to complete the first stage of our research strategy, we will have to construct multiattribute utility functions for the typical equipped driver and the typical nonequipped driver, as well as the managing operator, in order to test the robustness of the Pareto optimum arrangement in the ETC system design for the Crescent City Connection. Similar data collection and analysis will have to be performed for several ETC systems to obtain general guidelines and rules of thumb for all electronic toll collection systems.

5. Conclusions

We have been able to use the lessons learned from a quantitative approach to computer architecture to develop a new research strategy for IVHS system design, based on social decision analysis. The initial step taken to verify the strategy has been encouraging. We intend to propose specific work in the coming year to pursue the new research strategy.

6. References

Boyce, D.E., Kirson, A. and Schofer, J.L., "Design and Implementation of ADVANCE: The Illinois Dynamic Navigation and Route Guidance Demonstration Program," *Vehicle Navigation & Information Systems Conference Proceedings*, Part 1, IEEE/SAE, 415-426, 1991.

Chen, K., "Social Decision Making," course notes for a graduate course on quantitative approaches to decision making involving multiple persons, multiple objectives, uncertainties and time tradeoffs, Department of Electrical Engineering & Computer Science, University of Michigan, used continuously since 1980.

Chen, K., "Policy Implications of Driver Information Systems," TRB Paper 921016, presented at the 71st Annual Meeting of the Transportation Research Board, National Academy of Science, January 12-16, 1992a.

Chen, K., "Radical Approaches to IVHS Goals," *Proceedings of the 2nd Annual Meeting of IVHS AMERICA,* 1992b.

Chen, K. and Ervin, R.D., "Intelligent Vehicle-Highway Systems: U.S. Activities and Policy Issues," *Technological Forecasting and Social Change*, 38(4), 363-374, 1990.

Chen, K. and Underwood, S.E., "Integrative Analytical Assessment: A Hybrid Method for Facilitating Negotiation," *Negotiation Journal*, 4(2),183-197, 1988.

Chorafas, D.N., *Systems Architecture and Systems Design*, McGraw-Hill, 1989.

Halas, P.D., "A Road Pricing Scenario for a Simple Traffic Network: Achieving Network Optimal Solutions," a student paper, Department of Industrial & Operations Engineering, University of Michigan, 1991.

Hennessy, J.L. and Patterson, D.A., *Computer Architecture: A Quantitative Approach*, Morgan Kaufman Publishers, 1990.

Keeney, R.L. and Raiffa, R., *Decisions with Multiple Objectives: Preferences and Value Tradeoffs*, Wiley, 1976.

Rillings, J.H. and Lewis, J.W., "TravTek," *Vehicle Navigation & Information systems Conference Proceedings*, Part 2, IEEE/SAE, 729-737, 1991.

Stafford, F.P. and Chen, K., "Economic Aspects of Public-Private Partnerships for the Provision of Roadway Services," University of Michigan (IAB Report), May 1992.

Von Tomkewitsch, R., "Dynamic Route Guidance and Interactive Transport Management with ALI-SCOUT," *IEEE Transactions on Vehicular Technology*, 40(1), 45-50, 1991.

Appendix A

Performance Measures for IVHS Architecture

The following list of IVHS goals and objectives was prepared by the System Architecture Committee of IVHS AMERICA in May, 1991, as a basis for developing performance measures for IVHS architecture.

GOAL: *Increase the capacity and operational efficiency of the surface transportation system.*

OBJECTIVES:

1. Increase the volume of people and goods that can be moved on existing facilities and in corridors.
2. Increase the efficiency of use of available surface transportation system capacity.
3. Reduce time loss associated with surface transportation.
4. Reduce the amount of overall delay caused by incidents.
5. Reduce the delay associated with intermodal interchanges.
6. Reduce excess travel caused by navigation problems.
7. Reduce the amount of travel needed to satisfy economic and social needs.

GOAL: *Improve the safety of surface transportation.*

OBJECTIVES:

1. Reduce the number of fatalities and serious injuries.
2. Reduce the number of lesser injuries.
3. Reduce the number and cost of property damage accidents.
4. Reduce the number of secondary accidents associated with incidents.
5. Improve the responsiveness of emergency services.
6. Reduce the number of accidents associated with fatigue.

7. Reduce the number of drivers on the road under the influence of alcohol or drugs.
8. Improve the ability to identify and track hazardous material movements.
9. Enhance civil emergency warning systems.
10. Improve traffic safety law enforcement capabilities.

GOAL: *Reduce the environmental and energy impacts of surface transportation.*

OBJECTIVES:

1. Reduce harmful vehicle emissions.
2. Improve fuel consumption efficiency.
3. Reduce surface transportation energy consumption associated with fossil fuels.
4. Reduce new right-of-way requirements.
5. Reduce noise pollution.

GOAL: *Enhance mobility, productivity, and the convenience and comfort of the surface transportation system.*

OBJECTIVES:

1. Improve the mobility of disabled and elderly travelers.
2. Reduce the travel and operating costs incurred by all users and operators of fleets of vehicles.
3. Improve the quality of and access to information on travel options and replacements.
4. Enable travelers to make alternative use of their traveling time for work or leisure activities.
5. Reduce the level of stress associated with travel.
6. Improve travel time predictability.

GOAL: *Build systems that are affordable, credible, reliable, and easy to use.*

OBJECTIVES:

1. Ensure that systems are accessible by those at all income levels.
2. Provide information which is accurate and timely.
3. Minimize the number of system malfunctions.
4. Develop systems which are easy and safe for the public to learn to use.
5. Develop systems which are used in a uniform manner across North America, and to the extent possible, throughout the world.
6. Minimize the safety risk associated with using all system components, including necessary roadside hardware.

GOAL: *Improve administration of the surface transportation system.*

OBJECTIVES:

1. Reduce the costs associated with regulating roadway users.
2. Reduce the costs associated with regulating commercial vehicles.
3. Reduce the costs and improve the equity associated with collecting road taxes.
4. Reduce the costs and improve the efficiency of collecting fares, tolls and parking fees.
5. Provide a data base of information on the performance of the surface transportation system.
6. Improve roadway maintenance planning and service.
7. Speed the process through which new technology is incorporated into the surface transportation system.

Appendix B

Electronic Toll Collection at Crescent City Connection
(Interview with Mr. Euris Rodrigue of Lockheed)

Questions Prepared Before the Interview

A. <u>Before AVI was installed</u>

- How many drivers crossed the bridge per month?
- How many booths operated at various times?
- How much was the toll?
- How long were the queue and the waiting time?
- How much was the capital cost per booth?
- How much was the operating cost per booth?
- How much uncertainty was in the crossing time?
  (*i.e.*, how much time had to be allowed to cross the bridge?)

B. <u>After AVI has been installed</u>

- How many drivers use automatic vehicle identification (AVI)?
- How much do they pay for the AVI tags?
- How much toll do they pay?
- How long does it take equipped cars to go through?
- What percentage of equipped tags get misread?
- How long are the queue and waiting time for the unequipped cars?
- How many booths are saved?
- How much operating cost has been saved?
- How much uncertainty is there for each group in their crossing time?
  (*i.e.*, how much time is allowed to cross the bridge by each group?)

Results (Answers by Rodrigue)

- Electronic toll collection (ETC) using automatic vehicle identification (AVI) technology was installed in 1/89 when the bridge authority began to collect tolls for bridge crossing that used to be free.

- The ETC system was installed by Gulf Systems, Inc., which was acquired by Lockheed recently in 10/91.

- There are 12 lanes, 3 of which are dedicated to AVI, and the rest can be both manual and automatic.

- There are 30-40 collectors working 8-hour shifts per day.

- The AVI technology was designed to work reliably at 0-20 mph. The actual speed for nonstop toll collection averages around 5-10 mph.

- About 60,000 vehicles cross the bridge per month.

- The toll is $1.00 for manual collection, and $0.70 for ETC.

- ETC subscribers put $25 deposit for the tag and make $40 prepayment each time for the toll. The tag costs $32.

- Equipped vehicles crossing the bridge average around 20-25% of all vehicles, but are around 30% during rush hours.

- Gulf Systems and Lockheed are somewhat disappointed at the current market penetration (*i.e.*, percentage of equipped vehicles.) There have been two advertising campaigns (right at the bridge crossing for the unequipped drivers). Each campaign has produced a 5% increase of subscribers.

- Most commuters over the bridge are blue-collar workers who may find the initial outlay of $25+40=$65 too much for them to come up with. Some are not sure they will use the tags often enough to make it worthwhile. (Another installation exists near New Orleans near a white-collar commuting path, with much higher penetration.)

- The capital cost per booth is about $5,000-$10,000. In addition, it costs $1/2 million for installing manual PCs in all lanes (to log inputs and tolls), and another $1 million for the 12 AVI readers, plus a microVAX computer system that serves all the AVI readers.

- The reading is 99.5+% accurate.

- Each manual payment takes 4-20 seconds, depending on the complexity of the change. Average time is 8-10 seconds.

- Each booth can process 10 cars per minute manually, and 24 cars per minute with ETC.

- The average queue length during rush hours is 10-12 vehicles in the mixed lanes, and practically 0 vehicles in the dedicated lanes.

- The waiting time for the nonequipped vehicles is about the same with or without ETC as fewer booths are open when ETC is used. (That is, the nonequipped drivers may not get much benefit due to ETC.)

- The benefit for equipped drivers results not only from average time saved but also from reduction of uncertain delays at the booths. Nonequipped drivers normally allow 5 minutes to cross the bridge while the equipped drivers can allow only 1/2 minute.

- The cost savings for the bridge authorities have resulted mainly from the time savings, not so much from collecting tolls as from counting money. Money is counted 4 times in the manual toll collection process: the collector, the auditor, the accounting department, and the bank.

- The average labor cost for collectors is $4/hour, for auditors and accounting clerks is $6/hour. At the end of each shift, the collector takes 30-60 minutes to count money. About 20-30% of the time an auditor is needed to reconcile the difference between the recorded amount and the cash counted.

- An important benefit to the equipped drivers is that they need to pay only once ($40) while the nonequipped drivers have to pay 40-50 times for the same number of bridge crossings.

Social Decision Analysis (Preliminary Results)

- <u>Benefits for the equipped drivers</u>

Toll reduction = $0.30 per crossing
Assuming 2 crossings per work day, 240 work days per year, and 5% interest on the average capital outlay of $65:

Monetary savings = $0.30 x 480 - $65 x 0.05 = $140.70/year
Time savings = 5 minutes x 480 = 40 hours
At $8/hour, the total monetary equivalent savings
= $8 x 40 + $140.70 = $460.70/year

- Benefits for the nonequipped drivers

None, since the queues and their waiting times have not changed.

- Cost savings for the toll collection operator

The available data do not allow a complete assessment. The transition from manual to electronic toll collection also makes the situation much more complicated. However, the following preliminary (and conservative) calculation, which compares 100% manual versus 100% electronic toll collection from the perspective of the toll collection operator, should provide useful insight.

MANUAL VERSUS ELECTRONIC TOLL COLLECTION

Costs (annualized)	Totally Manual	Totally Electronic
1) Booths	\$10,000 x 9 x 10% = \$9,000/yr.	\$10,000 x 4 x 10% = \$4,000/yr.
2) Equipment	\$500,000 x 10% = \$50,000/yr.	\$1,500,000 x 10% = \$150,000/yr.
3) Collectors' Time	\$4/hr x 8hr/shift x 35 shifts/day x 365 days/yr. = \$408,800/yr	\$0/yr.
4) Auditor/Acc't Clerks' Time	\$6/hr x 1hr/shift x 35 shifts/day x 365days/yr. x 1.25 = \$95,810/yr.	\$0/yr.
5) TOTAL COST	\$563,610/yr.	\$154,000/yr.
REVENUE	\$1 x 60,000/mon x 12 mon/yr. = \$720,000/yr.	\$0.70 x 60,000/mon x 12 mon/yr. = \$504,000/yr.
SURPLUS	\$156,390/yr.	\$350,000/yr.

NOTES:

a) The above computation shows that, even with a toll discount, the surplus for ETC is twice as much as for manual toll collection.

b) All capital costs have been annualized at 10%.

c) The number of booths for manual operation is 9 in New Orleans. The number of booths for ETC is estimated to be 4, based on the ratio of 10:24 as the number of vehicles processed manually versus ETC during the same time interval.

d) Accounting clerks spend 1 hour per shift to count money; and auditors spend an average of 0.25 hour per shift to reconcile money counting. Collectors count money as part of their duties during their regular shifts.

e) The annualized cost of tags for ETC is roughly balanced by the interest generated by the required deposit and prepayment, and was therefore ignored in the above computation.

f) The above computation compared 100% manual versus 100% ETC. The mix of the two is harder to compute. However, it seems intuitively clear that the savings would increase monotonically as the number of equipped vehicles increases, although the relationship is not necessarily linear.

- Complete Social Decision Analysis

The above preliminary results illustrate the mutual benefits of electronic toll collection for both the equipped drivers and the toll collection operator. However, the robustness of the Pareto optimum arrangement cannot be tested without further data to construct multiattribute utility functions of the major interested parties.