Road Powered Electric Vehicle Technology Study (Saints Road Project)

Volume II: Test Reports with Data Sheets
### Volume II of this study

Volume II of this study is a compilation of test reports that result from a 10-month evaluation of E-TRAN Road Powered Electric Vehicle technology to determine operational safety and system durability/reliability; technology effectiveness; snow and ice removal requirements; and cost effectiveness. The test reports identify several areas for further study and development.

Through a series of theoretical and laboratory tests, this evaluation concludes that the E-TRAN RPEV concept remains sound in theory, but as tested under the current design, the system does not yet provide a safe and reliable transportation power alternative. The study addressed some findings of a previous report (No. MN/RC 93/03). However, the system design is still an immature technology under development, and must address significant safety and practical problems. Especially, the system must be made more robust and resistant to stresses and conditions found in a northern public roadway environment.

A laboratory test indicated a 46 percent reduction in energy consumption compared to gasoline power. The E-TRAN RPEV concept holds further promise as a possible solution to the limited range and energy efficiency of battery-powered vehicles.

Volume I presents summary results and also provides conclusions and recommendations to focus on future development of identified safety and technical design areas.

### Abstract (Limit: 200 words)

The St. Cloud Metropolitan Transit Commission served as contracting agent for this study. The other report in this series is MN/RC - 97/07 VOLUME I: RESEARCH SUMMARY.

### Security Class (this page)

Unclassified
ROAD POWERED ELECTRIC VEHICLE TECHNOLOGY STUDY (SAINTS ROAD PROJECT)

Volume II: Test Reports with Data Sheets

Final Report

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The contents of this report reflect the views of the authors who are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the views or policies of the Minnesota Department of Transportation.
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Table of Contents

Volume I: Research Summary

Executive Summary
General Introduction ......................................................... 1
   I. Report Purpose ...................................................... 1
   II. Problem Description .............................................. 1
   III. Report Scope and Limits ........................................ 1
   IV. Overview of Report Organization and Evaluation Process ............. 2
   V. Conflict of Interest ................................................ 3
Summary Results of Specific Tests ........................................... 5
Needs for Further Study .................................................... 11
Glossary of Abbreviations .................................................. 13
Appendix A  E-TRAN System Description
Appendix B  Preliminary Engineering Review
Appendix C  Evaluation Plan
Appendix D  Sample Test Plans

Volume II: Test Reports with Data Sheets

Safety Test 1A - Power Strip Loses Power
Safety Test 1C - Short Circuit Of Strip
Safety Test 1D - Damaged Insulating Segment
Safety Test 1G - Gasoline On Strip
Safety Test 2 - Short Endurance Runs
Safety Test 3 - Corrosion
Safety Test 4 - Signal Interference
Safety Test 5 - Factors Resulting In Shock
Safety Test 6 - Human Interaction
Safety Test 7 - Effect On Road Drainage
Technology Test 1 - Dynamometer Tests
Technology Test 2 - Adverse Performance Conditions
Snow & Ice Tests
A Cost Comparison Study Of Three Electric Transit Options
1.0 INTRODUCTION

1.1 The E-TRAN road powered electric vehicle (RPEV) receives electrical energy from the rail on the road surface. The vehicle uses the energy to power the vehicle. It can also store electrical energy in a battery onboard the vehicle. The RPEV uses electricity from the battery when it is not in contact with an electrified rail.

1.2 This test was designed to answer the question about how well does the RPEV perform when a certain percentage of electrified rail is off.

1.3 In addition to the investigation described above, the investigators took this opportunity to measure the contact bounce experienced between the pantograph and the rail. This was measured with an oscilloscope and is also reported here.

2.0 THE TEST

2.1 The testing was performed on the E-TRAN simulator located at the St. Cloud Technical College. The simulator consisted of a circular track with 3 electrically separated switched segments. System voltage was 330 VDC. A modified Isuzu Trooper was used as the vehicle. The Trooper was modified by installing a 15 HP electric induction motor driven by a solid state adjustable speed drive. The Trooper was equipped with a pantograph system which contacted the electrified rail allowing electric power to flow to the Trooper's motor. The Trooper also had an onboard battery connected to deliver 330 VDC to a DC bus. The onboard battery consisted of 25 six-cell units connected in series to achieve 325 volts maximum. The cells were rated 6.5 Ah with a peak current of 8A. The input to the adjustable speed drive and the pantographs were also connected to the DC bus. See Figure 1A-1. This arrangement gave the system continuity of power. Under normal conditions, the pantograph/electric rail provided enough power to run the motor to drive the Trooper and also to charge the battery. If the pantograph/electric rail system was not able to deliver power, the battery supplied the power and the Trooper continued to go.
2.2 The test consisted of turning off certain rail segments and observing if the pantograph/electric rail could deliver enough electricity to power the Isuzu Trooper and maintain the charge on the battery. The simulator was tested with all rail segments off, 2/3 of the segments off, and 1/3 of the segments off.

The starting and stopping times were recorded as well as distance traveled. Starting and stopping voltages of the battery were recorded as a measure of the effectiveness of power delivery. If adequate power was being delivered, the battery remained fully charged at approximately 320 VDC. If adequate power was not being delivered, battery voltage declined. At approximately 290 VDC the system turned off because of an automatic low voltage shutdown protective circuit in the adjustable speed drive.

2.3 The test measuring pantograph contact bounce consisted of measuring the voltage input from the pantograph/electric rail at the line side of the full bridge rectifier onboard the Isuzu Trooper. The rectifier isolated the voltage measurement from the battery voltage. The voltage fluctuations were observed with a Fluke 95 Scopemeter. This instrument has a waveform storage function which allowed waveforms to be "frozen" and displayed for analysis. Pantograph contact bounce was not a regular periodic function; however, this storage feature allowed samples to be taken and averages discerned.
E-TRAN Road Powered Electric Vehicle

Date: 3-24-95
Time: 1PM
Location: St Cloud Tech College
Recorder: Nick Musachio
Position: Technical Director

<table>
<thead>
<tr>
<th>Test Run No. 1</th>
<th>Start Time</th>
<th>Stop Time</th>
<th>Distance Travelled</th>
<th>Battery Voltage Start</th>
<th>Battery Voltage Stop</th>
<th>Vehicle Ave Speed</th>
<th>Vehicle Weight</th>
<th>System Condition</th>
<th>General Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Batt fully charged, track off</td>
<td>4:20PM 3-24-95</td>
<td>4:32PM</td>
<td>1.2 miles</td>
<td>325V</td>
<td>291V</td>
<td>6mph</td>
<td>3000lbs</td>
<td>Good</td>
<td></td>
</tr>
<tr>
<td>Test Run No. 2</td>
<td>10:30PM 3-23-95</td>
<td>11:55PM</td>
<td>7.0 miles</td>
<td>318V</td>
<td>316V</td>
<td>6.5mph</td>
<td>3000lbs</td>
<td>Good</td>
<td></td>
</tr>
<tr>
<td>Batt fully charged, 1/3 track off</td>
<td>1:20PM 3-24-95</td>
<td>4.2 miles</td>
<td>326V</td>
<td>295V</td>
<td>6mph</td>
<td>3000lbs</td>
<td>Good</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Test Run No. 3</td>
<td>Batt fully charged, 2/3 track off</td>
<td>8.3 miles</td>
<td>288V</td>
<td>309V</td>
<td>7mph</td>
<td>3000lbs</td>
<td>Good</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Test Run No. 4</td>
<td>Battery partially charged, 1/3 track off</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Vehicle ran strongly during entire test.
Near the end test, the electric motor stopped in off sections and restarted on powered section. Motor stop was due to low voltage cut-out feature on.

Figure 1A-2
3.0 THE RESULTS

3.1 The data recorded from the tests are presented in Figure 1A-2.

3.2 Test Run No. 1 data shows how far this vehicle can travel with a fully charged battery and no power from the rail. The vehicle traveled 1.2 miles before the battery voltage dropped below the threshold necessary to maintain the vehicle's adjustable speed motor drive.

3.3 Test Run No. 2 tested simulator performance with 1/3 of the track not operational. The simulator ran for 7.0 miles for a period of 25 minutes. The battery maintained its charge and the vehicle ran normally throughout the test.

3.4 Test Run No. 3 tested simulator performance with 2/3 of the track not operational. The simulator ran for 4.2 miles before the battery voltage dropped below the low voltage threshold. At the end of the test, the vehicle would shutdown in the unpowered sections and coast to the powered section. When it reached the powered section, it could accelerate to the end and then coast through the unpowered sections again.

3.5 Test Run No. 4 was a reverse of Test Run No. 2. Like Test Run No. 2, 1/3 of the track was not operational. The reverse was that in this test, the battery was not fully charged. After approximately 8.0 miles of testing, the simulator was stopped. The battery voltage was measured and was found to be higher, 309V, than at the beginning of the test, 288V.

3.6 Contact bounce was measured by measuring the input voltage from the rail into the Trooper and observing voltage interruptions. The interruptions were non-periodic and therefore a stable scope trace was not possible to achieve. The investigators overcame this by randomly storing traces with the oscilloscope's storage feature. By observing several stored traces, investigators were able to determine consistent patterns of pantograph contact bounce. Contact bounce was first measured as the vehicle traveled at 5 mph. The average was 1 bounce per millisecond or an average of 1,000 bounces per second. The vehicle speed was increased to 12 mph. At this speed, the average increased to 4 bounces per millisecond or 4,000 bounces per second.
4.0 CONCLUSIONS

4.1 The results of the tests show that the E-TRAN simulator as presently configured can operate indefinitely with only 67% of the track operational. A 67% operational track not only powers the vehicle but is capable of charging the vehicle battery at the same time.

4.2 Somewhere between 33% and 67% of operational track with a vehicle speed of 6 mph, a threshold is crossed and indefinite operation can no longer be maintained. It must be noted that this threshold is variable and is dependent on the constantly changing amount of power required by the vehicle for such things as:

1. Overcoming the wind resistance of higher speeds.
2. Accelerating.
3. Climbing up hills.
4. Battery condition.

4.3 The threshold of indefinite operation is defined by the difference between the average amount of electric power needed by the vehicle (P\textsubscript{NEED}) and the average amount of electric power that can be delivered by the rail/pantograph (P\textsubscript{DEL}).

If P\textsubscript{DEL} - P\textsubscript{NEED} > 0, the vehicle can operate indefinitely.

If P\textsubscript{DEL} - P\textsubscript{NEED} < 0, eventually the vehicle will deplete the energy in the batteries and stop.

If P\textsubscript{DEL} - P\textsubscript{NEED} = 0, then P\textsubscript{DEL} = P\textsubscript{NEED} \text{ P\textsubscript{THRESHOLD}}.

4.4 As stated above, P\textsubscript{THRESHOLD} is constantly variable because P\textsubscript{NEED} is variable. Literally, it is as variable as the wind. A gust of wind head on into a vehicle can increase its need for power. However, worst case scenarios are definable which can be used to define a maximum P\textsubscript{NEED} for engineering purposes. P\textsubscript{DEL} is variable as well. Some parameters which effect P\textsubscript{DEL} are:

1. Vehicle speed.
2. Track condition.
3. Pantograph design.
4. Pantograph condition.
5. Weather.
4.5 The basic idea from the foregoing paragraphs is that parameters that affect the transfer of power from the rail to the vehicle will limit the performance of the vehicle. For example, there is a maximum speed beyond which the vehicle cannot go. That maximum speed depends on many variables but eventually the vehicle will reach a point where it is taking all the energy possible from the rail and therefore, it cannot go any faster. That speed might be 200 mph or it might be 20 mph depending on design and environmental conditions. Another example is the maximum rate of acceleration. The ability to efficiently transfer power from the rail to the vehicle is an area that has not been investigated yet, but which will be a very important issue in the design of larger systems.

4.6 An area for future study is improvement of the power exchange efficiency between the pantograph and the rail. Contact bounce disrupts the flow of power into the vehicle and decreases $P_{DEL}$. It also increases system energy loss. Reducing contact bounce is one way to improve system efficiency and reliability.
E-TRAN ROAD POWERED ELECTRIC VEHICLE
SAFETY TEST 1C REPORT

EEA PROJECT NO. 3843
APRIL 5, 1995
WILLIAM F. THIESSE, PE

1.0 INTRODUCTION

1.1 The E-TRAN rail segments (positive and negative) are designed to be electrically isolated from the road surface (ground) and each other. There are two reasons. First, the electrical isolation, particularly isolation between the rail segments and ground, offers some protection to humans who may inadvertently contact a rail segment. Second, electric current leakage between positive and negative rail segments is directly proportional to the amount of electrical isolation between them. This leakage current is lost energy in the system.

1.2 The purpose of this test was to attempt to quantify the changes in electrical isolation (resistance) between the rail segments and ground when foreign materials such as salt water come in contact with them.

1.3 The test was intended to give order of magnitude quantities for a short sample of track (approximately 8 feet total length). The resistance quantities obtained are representative of changes in resistance between different system components. However, care should be exercised if these resistances are used in calculations for such things as energy loss. The rail sample used was very short and track length, segment length, road surface material, and track configuration are some parameters not studied here that can change system resistances significantly.

2.0 THE TESTS

2.1 The test was conducted on an 8 foot length of track. The sample had two 4-foot rail segments separated by a 2-inch gap. The gap was filled with silicone caulk. The rail sample was laid on an exterior concrete slab located near the test simulator at St. Cloud Technical College. A
A masonry nail was driven into the concrete to provide a connection point for ground potential (ground electrode).

2.2 Resistances in the megohm range were measured with an Associated Research megohmmeter. Resistances in the kilohm range were measured with a Simpson Model 260 multimeter. Leads were connected directly to the two rail segments to facilitate meter connections.

2.3 Seven separate tests were conducted. Three measurements were taken for each test. The three measurements were:

1. Resistance between positive and negative rails (P-N).
2. Resistance between positive rail and ground electrode (P-G).
3. Resistance between negative rail and ground electrode (N-G).

See Figure 1C-1.

2.3.1 Test No. 1 was the control. The concrete surface was dry and no foreign material contacted the track.

2.3.2 Test No. 2 introduced a piece of steel which was placed to contact the negative rail and the concrete. The steel was approximately 1 foot long and 2 inches wide.

2.3.3 Test No. 3 introduced a second piece of steel which contacted the positive rail and the concrete. The second piece of steel was similar to the first.

2.3.4 Test No. 4 consisted of pouring salt water over the length of one rail (the positive). The metal from tests 2 and 3 was not present. The measurements were taken after the salt water had been poured while the rail segment was still wet. The salt water solution was approximately 1 cup of salt to 2 gallons of tap water.

2.3.5 Test No. 5 was similar to test no. 4 except salt water was poured the length of the rail over both rail segments.

2.3.6 Test No. 6 was the same as test no. 4 except tap water only was used. No salt was present.
FIGURE 1C-1
2.3.7 Test No. 7 was the same as test no. 5 except tap water only was used. No salt was present.

2.3.8 During the testing, it became obvious that performing the tests out of sequence from the original plan would give more control. Tests 6 and 7 were performed before tests 4 and 5. This assured that no residual salt was present during tests 6 and 7, which used only tap water.

2.3.9 The measurements were recorded and are included in the data collection sheets, Figures 1C-2 and 1C-3.

3.0 THE RESULTS

3.1 The results clearly show the effects of having different conducting materials come into contact with the rail. There are, however, some apparent inconsistencies. For instance, in test no. 6, resistance to ground for the positive and negative rail segments was 75 k and 30 k, respectively. The measured resistance between the positive and negative rail segments was 11 M. Electrical circuit theory would predict a value closer to 100 k (30 k + 75 k = 105 k). These inconsistencies can be explained by recognizing that the measurements were not made under environmentally controlled conditions and that resistance measurements in this range are difficult. The purpose of the testing was not to produce absolutely accurate results but rather to spot trends which would warrant further study. The results were not reviewed during testing for consistency with circuit theory.

3.2 The results show that introducing conducting materials in contact with the rail lower resistance between the rails and between the rails and ground. The metal appeared to have the least effect but this is probably because of the difficulty of establishing solid contact between the metal and the dry concrete surface.

Tap water lowered the resistance substantially. When water was applied, the megohmeter could no longer be used because the resistance dropped by a factor of approximately 1,000 (three orders of magnitude). The application of salt water reduced the resistances further.
4.0 CONCLUSIONS

4.1 Metal contacting both the rail and concrete simultaneously did not reduce resistance significantly. Measured values remained in the range of several megohms to tens of megohms. This result probably is due to poor electrical contact between the metal and the dry concrete.

4.2 Moisture in contact with the system changes the resistances significantly. The idea that the system can remain effectively ungrounded during conditions of high moisture such as rain storms and snow storms appears to be unfounded. It is arguable that the measured resistances were still high enough to limit electric current to levels which are safe for humans. However, the tests suggest that resistance could be lowered to levels below the threshold of safety under certain circumstances. Ponding of water and salt water was not investigated and this condition could lower resistance significantly further.

4.3 The lowering of resistances because of moisture has an impact on system losses. Lowering resistance by a factor of 1,000 means leakage current increases by a factor of 1,000. These tests were not designed to accurately measure system losses but it is a topic that appears ripe for further investigation. Preferably further investigation would be performed on a longer length of track which would better represent the system.

4.4 One of the arguments for an ungrounded system was that electrical isolation reduced the risk of electric shock to people coming into contact with an energized electric rail. This test demonstrated that such an argument is invalid under certain conditions which occur naturally in the environment of the track. Using an ungrounded system does not reliably decrease risk to humans.
E-TRAN Road Powered Electric Vehicle
Safety Test 1C
Data Collection Sheet

<table>
<thead>
<tr>
<th>Test Number</th>
<th>Resistance</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test No. 1</td>
<td>P-N 50M-Ohm</td>
<td>One foot by two inch piece of steel was placed on track in contact with concrete.</td>
</tr>
<tr>
<td></td>
<td>P-G 50M-Ohm</td>
<td></td>
</tr>
<tr>
<td></td>
<td>N-G 10M-Ohm</td>
<td></td>
</tr>
<tr>
<td>Test No. 2</td>
<td>P-N 75M-Ohm</td>
<td>Piece of steel similar to steel used in test no.2 was placed on second rail.</td>
</tr>
<tr>
<td></td>
<td>P-G 100M-Ohm</td>
<td>One piece contacted the positive rail and concrete, the other piece contacted the negative rail and concrete.</td>
</tr>
<tr>
<td></td>
<td>N-G 7.5M-Ohm</td>
<td></td>
</tr>
<tr>
<td>Test No. 3</td>
<td>P-N 75M-Ohm</td>
<td>Solution was approximately one cup rock salt to two gallons of tap water.</td>
</tr>
<tr>
<td></td>
<td>P-G 45M-Ohm</td>
<td>Salt water was poured over the length of one rail from a small container.</td>
</tr>
<tr>
<td></td>
<td>N-G 80M-Ohm</td>
<td></td>
</tr>
<tr>
<td>Test No. 4</td>
<td>P-N 300K-Ohm</td>
<td>Solution was approximately one cup rock salt to two gallons of tap water.</td>
</tr>
<tr>
<td></td>
<td>P-G 26K-Ohm</td>
<td>Salt water was poured over the length of each rail from a small container.</td>
</tr>
<tr>
<td></td>
<td>N-G Not</td>
<td>recorded</td>
</tr>
<tr>
<td>Test No. 5</td>
<td>P-N 5K-Ohm</td>
<td></td>
</tr>
<tr>
<td></td>
<td>P-G 22K-Ohm</td>
<td></td>
</tr>
<tr>
<td></td>
<td>N-G Not</td>
<td>recorded</td>
</tr>
</tbody>
</table>

General comments
Ground was established by driving a masonry nail into the concrete slab.
MegOhm resistances were measured with an Associated Research megohmmeter (megger).
KiloOhm resistances were measured with a Simpson Model 260 multimeter.

Figure 1C-2
E-TRAN Road Powered Electric Vehicle  
Safety Test 1C  
Data Collection Sheet

<table>
<thead>
<tr>
<th>Test Number</th>
<th>Resistance</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test No. 6</td>
<td>P-N 1M-Ohm</td>
<td>Water was poured over the length of one rail from a small container.</td>
</tr>
<tr>
<td>Mist water</td>
<td>P-G 75K-Ohm</td>
<td></td>
</tr>
<tr>
<td>onto one</td>
<td>N-G 30K-Ohm</td>
<td></td>
</tr>
<tr>
<td>rail</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Test No. 7</td>
<td>P-N 100K-Ohm</td>
<td>Water was poured over the length of each rail from a small container.</td>
</tr>
<tr>
<td>Mist water</td>
<td>P-G 90K-Ohm</td>
<td></td>
</tr>
<tr>
<td>onto both</td>
<td>N-G 80K-Ohm</td>
<td></td>
</tr>
<tr>
<td>rails</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Safety Test 1D: Damaged Insulating Segment

Principle Investigator: Mike Lehn, SCTC
Technical Director: Nick Musachio
Observer: Roger Young, Instrumentation Instructor
April 20, 1995

Research issue: The E-TRAN system uses a series of powered conductor segments. In this test they are 5 feet long with 3 inch insulating segments separating them. (See photos) The insulating segment serves several purposes:

1) **Electrical**: it electrically separates two negative and positive poled conductive segments,
2) **Structural**: it carries the weight of the pantograph in the transition between the two conductors, and physically separates the conductors.
3) **Protective**: in the prototype system, it acts as a conduit for electric wires.

In this test, a three inch long insulating segment between two power strips is purposely removed, and the vehicle is run repeatedly over the damaged section to observe the effect of the missing insulating segment. Speeds from one to ten miles per hour were tested. Higher speeds were not tested due to the limited radius of the simulator. The test run was approximately 100 revolutions, which is equivalent to approximately 3 miles, speeds varied from 2 mph to 9 mph.

Results: The test run indicated that the rubber base of the strip carried the pantograph in the absence of the insulating segment. The upper ridges of the base that normally enclose the conductor acted as supports for the pantograph allowing the system to work normally. (See illustration). This did not affect the performance of the vehicle in the short term. However, as noted before the insulating segment serves three purposes, structural, insulating and protective. Since the insulating gap also acts as a conduit, removing the insulator exposes the current carrying wires inside. Thus, the electrical insulating and protective features were diminished by the absence of the insulating segment thus leaving the conductive wires exposed to weather and wear.

Additional note: In another test executed by John Palmer, as noted in safety test six, the integrity of the strip was compromised by braking directly on top of the system. In this case a poor bond between the conductive strip and the rubber base resulted in the conductive strip sliding forward in the rubber base. In an active strip this would affect both the operation and safety of the system.
Conclusion: The structural integrity of the power strip plays an integral role in the functioning of the system. Damaged sections, missing sections, or weak bonds between the conductive strip and the insulating base pose operational and safety risks.

Recommendations: The prototype system as presented will not function operationally or safely with missing insulating segments. The prototype system tested would need much strengthening to maintain its adhesion to the road, the adhesion of the components to each other, and the structural integrity of the power strip in light of the powerful forces present on roadways especially the shearing forces posed by vehicles in a hard brake. Redesign and road testing should be done to assure the structural integrity of the system to assure that the conductive strips and the insulating segments will not break loose from the rubber base. Testing of various bonding materials and fasteners will be necessary.

If further testing indicates that the insulating segments separate, the following design modifications would be recommended:
1. Have the ends of the conducting segments tapered so that the pantograph load would be carried by the rubber base.
2. Redesign the wiring so that in the absence of an insulating segment, the conductor wires would not be exposed to wear by the pantograph system. The wires should be buried into the rubber insulating base or the pavement.

Steps needed for Implementation:
The steps for implementing the recommendations would be:
1) Road test system to determine the viability of the current design. If the current design cannot sustain wear with out losing insulating segments, then:
2) Strengthen design so that the possibility of losing a insulating segment is remote, and, or,
3) Redesign wiring so that it is not exposed in the absence of a missing insulating segment.
4) Redesign end conductors so that in absence of an insulating segment the ends of the conductors are tapered so the insulating base can carry the pantograph in absence of a insulating segment.
Safety Test 1G: Gasoline Fire

P.I. Nick Musachio
Technical Assistance Thomas Harens
April 20, 1995

Research Issue: This test was designed to answer the question of whether or not the E-TRAN system would ignite combustible materials spilled on the roadway. The event in which this would happen would be for example a gasoline truck turn over, or a car accident in which the gasoline tank ruptured, spilling gas on the road. Common oil and fluid drips from automobiles should not pose a hazard. Empirical evidence shows that roadways - although lightly coated by dripping oil, coolant, and gasoline, and various automobile fluids - as a rule do not ignite from dragging and sparking mufflers, or dragging and sparking chains, or cigarettes being thrown out the window.

This research question arose as a result of the observation that the E-TRAN system uses a sliding brush type current collection system that can be expected to spark and arc. This sparking is not generally visible during daylight. However, when observed at night sparking can be seen to occur regularly. Sparking seems to be inherent in all types of sliding contact type vehicles from trains, to trolley buses, to subways. The amount of sparking is dependent upon the quality of the connection, the voltage of the track, downward pressure of the contact, amount of current drawn, and speed of the vehicle. It can be affected by debris, sand, dirt, rocks, et cetera. The sparking is a presumed risk in the ignition of combustibles.

In this test gasoline was poured onto the power strip to determine whether or not the test vehicle would start a fire on the roadway. The test results proved only that ignition is neither assured nor impossible. Several amounts of gasoline starting with a one cup and progressing to one half gallon of gasoline were poured directly on the strip and the vehicle was driven over the area of the spill.

This research also seeks to address the question of the probability of a gasoline spill. A literature search was done to determine the statistical probability of a gas spill.

Results: After dozens of passes the gasoline did not ignite as a result of the passing over of the vehicle. Even when the maximum amount of gasoline was on the strip there was no ignition.
In an unrelated, later test, residual gasoline did ignite. Tire agitation had spread a small amount of gasoline. This residual gas ignited in a line about six feet long, six inches wide, and 12 inches high. It was quickly put out with snow. This ignition was due to sparking caused by internal arcing of unsealed pressure contact wires on the prototype track. This type of arcing would not be present in a system with solder or sealed connections.

In spite of the risk of combustion, it is difficult to predict the probability of a gas spill. MN/DOT's literature search found no statistics on the frequency of gasoline spills.

**Conclusions:** Ignition of combustibles spilled on an E-TRAN system is neither assured nor unassured. Vehicles carrying combustibles do occasionally overturn. The prototype system which used pressure connections that were unsealed and unsoldered is flawed. This type of connection poses an unnecessary risk of combustion of flammable liquids on the roadway.

**Recommendations:** Although ignition of gasoline spilled on the E-TRAN system is not assured, it certainly is a possibility in the event of a gasoline spill. Things that will prevent ignition are:

1. Driver education. Instruct drivers to stay alert and stay away from spilled combustibles. Avoid driving near gasoline spills if they are seen. They would most likely be near an overturned tanker truck, or a crashed automobile, easily identifiable markers. Recommend drivers switch to battery power if near a combustible source.
2. Vehicles carrying combustibles should avoid driving on E-TRAN roadways if any risk of spilling is present i.e. steep hills, high speeds, snow, sharp corners, etc.
3. Soldered or sealed connections should always be used to avoid the risk of combustion of flammables.

**Steps needed for implementation:**
Prevention of ignition of combustibles can be avoided by following these steps.
1) Steer around gasoline spills. Do not attempt to drive through spilled combustibles.
2) Design pantograph system to broaden contact or with multiple contacts so that good electrical contact minimizes arcing.
3) Require sealed and or soldered connections of conductive strips to power buses.
4) Trucks carrying flammables should not drive near E-TRAN systems if a turn-over or spill is remotely possible.
Safety Test 1 G
Gasoline Fire
Data Sheet

3/9/95, 2:00 PM
St. Cloud Technical College
Nick Musachio, Technical Director, Thomas Harens, Contract Manager

Conditions: Wet conditions from melting snow, sunny, 35 degrees.
Procedure: Gasoline is poured over track and spread. Vehicle drives around circle to determine if combustion occurs.

<table>
<thead>
<tr>
<th>#</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1 cup of gas poured onto strip No ignition 12 rounds of vehicle</td>
</tr>
<tr>
<td>2</td>
<td>Gas added to 1 quart level No ignition 12 rounds of vehicle</td>
</tr>
<tr>
<td>3</td>
<td>Gas added to 1/2 gallon level No ignition 12 rounds of vehicle</td>
</tr>
</tbody>
</table>

Observation: Vehicle running over strip did not cause fire.
In an unrelated incident some of the remaining gas caught on fire from sparking associated with evaporating salt water on the strip.
Fire was quickly put out without incident.

Recommendation: Although the E-TRAN system may not catch gasoline on fire, it is certainly not a good idea to drive through a gas spill with system.
It would be best to drive around gas spill, as common sense would dictate.
As is the nature of trolley type systems, they do spark regularly. Ignition of volatile combustibles is a probability.
Safety Test 2: Endurance Runs

P.I. Mike Lehn
Technical Director: Nick Musachio, John Flaschenriem Tech. Assistant
Observer: Roger Young, Instrumentation Instructor SCTC
April 23, 1995

Research Issue
This test was designed to determine the effects of prolonged use on the system. It answers the questions: What wears out and when? Will the system fail? If it does, in what manner and what components will fail? The test involved running the Isuzu Trooper test vehicle for extended periods on a simulator. The simulator, which was built for the study, puts intense use onto the sensing, switching, and roadway power strip components of the system. The simulator is circular and 150 feet in circumference. It consists of thirty stainless steel conductors, each five feet long, separated into three fifty foot long switched sections. Each mile on the simulator equals 35 revolutions.

The Husky Shuttle makes approximately 11,000 trips in one year’s time around a 1.6 mile loop. Each section of the track would receive 11,000 uses and 11,000 switching cycles. This would equal 11,000 revolutions on the simulator which is the equivalent of 314 total miles. Thus, 314 miles would simulate one years worth of switch cycling and strip wear if the Husky Shuttle were the comparison.

While the simulator intensively cycles the roadway portions of the system, the simulator does not amplify wear of vehicle components. Specifically the collector brushes which slide across the conductive strips embedded into the roadway. Measurements were taken of the wear components on the vehicle which are the three collector brushes on the pantograph. These are the components that slide along the track and collect electricity from the conductive strips on the roadway.

The collector brushes are softer than the strips and therefore wear more quickly, and are a replacement part. These components are presumed to wear in a linear manner, i.e. the collector brushes wear at an even rate. For example, if they wear 1 millimeter in one hundred miles, they should wear two milliliters in two hundred miles, and three millimeters in three hundred miles, and so on. Thus, by measuring wear during endurance runs, one can predict wear rates for given materials. The material used was a copper/graphite brush manufactured from an overhead crane.
brush. The material was chosen because of its self lubricating qualities and its tensile strength which allows it to receive impacts without breaking.

**Sensing and switching** in the system can be accomplished in a number of different ways with differing sensors and switching devices. The sensing and switching scheme chosen for the simulator is described thusly: Sensing is achieved by solid state magnetic inductive sensors, which are triggered by a series of magnets beneath the vehicle. These activate a timed relay which activates a given portion of the track. The main power turn on/off components are SCR diode packs which are triggered by a 12 volt signal from the sensing module. These components were observed during the testing periods.

The test design prescribed 5 three hundred mile endurance runs for a total of 1500 miles. Although the mileage was attained over the year, due to a variety of factors the tests were not carried out precisely as prescribed. This should not effect the results nor conclusions.

**Results**
The system has in the early endurance runs worked for extended periods of time. It traveled for one thousand and three miles without failing during a period of five days in October 1994 operating in weather varying from clear to heavy rainstorms.

A post run inspection showed extensive wear on the rubber gaps separating the stainless steel conductive strips (see photos), and wear on middle areas of the collector bars. The stainless steel conductive strips showed no wear when measured with a micrometer. At a later date in a corrosion study some wear was found which occurred unevenly along the conductive strips. (See corrosion report.) The wear on the collector bars occurred in the middle of the bars and not on the outer edges. The system was voluntarily shut down 1,003 miles, which is the equivalent of over three years wear on the Husky Shuttle. The major electronic components, the sensors and SCR switching diodes functioned well.

During runs in March, the pantograph wear was uneven. (See photo) Most wear was, as predicted, in the center of the collectors where contact with the conductive strips was heaviest. This run was followed by another run in April of 530 miles with similar results. These runs varied from the test design, since they sometimes took several days and mileage points would
occur during the nighttime or weekend hours. Due to time, resource constraints, and construction at the research site, the entire test regimen was not completed.

Wear on the pantographs varied from 1 millimeter to no wear in 400 miles. At these rates a 30 mm. thick collector brush could be expected to last 12,000 miles at least before servicing. A likely service scenario would be to use segmented collector brushes, then inspected and rotate on a regular basis.

During the March test runs, which were done in extremely cold weather, reaching -15 F, the system operated for a series of runs of totally 379 miles over a series of four days before stopping due to resistors heating melting solder connections, causing two of three power switches to fail to power. Upon replacement of the resistors the system functioned properly. The malfunction could be considered a result of failed thermal management. As well, it could be considered a result of the intense use given to the systems by the simulator. Had the cycling been less frequent the resistors could have cooled more which would have prevented the malfunction. In the April test the resistors were thermally managed by the use of a heat sink and the problem did not recur. The system ran for several days without recurrence of the problem.

Since the technology has no precedents and uses specific components literature offers few predictions of the systemic durability. On a component level, according to the manufacturers, the electronics being of a solid state nature are considered indefinitely reliable unless they are physically damaged, too much voltage is applied, or they are overheated. The pantograph collector mechanism can be compared to an electric train collector. Schunck Graphite, a manufacturer of these mechanisms, obtains 70,000 miles of wear on their overhead collector brushes. Wear of the other components cannot be easily predicted.

**Conclusions**

In all, the system tested shows theoretical viability under varying conditions and under intense use.

**Sensing:** In general the sensing system worked well. It can be concluded that the electronic components will function well if they can be protected and the wiring leading to them can be protected. Protection of the wiring will be key to a reliable system.
Switching: The test results indicate that proper thermal management - cooling - is a must for any system. Overheating can and will cause component failure and must be avoided at all costs. Solid state components will work indefinitely if they never overheat. Overheating is preventable with proper design. In the simulator passive cooling was used (no fans, just heat sinks). It would be advisable to consider: 1) fan cooling, 2) heat sensing auto shut down, 3) current sensing 4) over size components for worst case scenarios, 5) resettable fusing.

The conductive strips: Stainless steel holds up well with the copper graphite collector brush. Little wear or corrosion was present after the endurance runs.

The insulating gaps: The use of rubber for the insulating gaps does not appear to be the best solution for sustained wear. (See photo). Some of the insulating segments showed signs of severe wear. Several insulating gaps were Delrin, a type of abrasion resistant plastic similar to nylon. These insulators wore much less severely.

The Pantograph/ collector brushes: The wear pattern on the brushes was uneven, as could be expected, since the strips made contact repeatedly in the same areas. Experience shows that the amount downward pressure on the collector bars appears to affect the wear rate of the bars as well as the insulating gaps. Too little the system does not run properly, too much and excessive wear occurs. Determining the proper amount of pressure will be important from both a functional and maintenance point of view. Continued use of segmented current collectors is recommended since worn areas can simply be replaced without replacing the entire brush. Further study should improve the wear rate of the collector bars since electric train collector brushes typically travel 70,000 miles between change outs. Improved life should be possible with further study of materials, lubrication, and downward pressure rates. Clearly, pantograph design and components will be a key area of study in the future.

General comments: Some of the problems which showed up in the system are a result of the intense use put to the system by the simulator which caused overheating of the switching components. These problems would not occur in normal operations. However, problems which did arise indicate the importance of proper component design and selection.
**Recommendations**

From the study the following recommendations can be made:

1) **Sensing**: Care should be taken to safeguard the wiring and physically protect the components.

2) **Switching.** Thermal management must take center stage in designing future systems if solid state switching is to be used. Heat is the number one enemy of electronic components. A fused and short circuit proof switching system must be incorporated into designs.

3) **Pantograph**: This area will require further research as to determining the proper amount of downward pressure on the pantographs. From experience varying pressures will affect both the wear rate and the amount of electricity which can be picked up. It is likely, that a variable tensioning system will be desirable. Working in conjunction with an electric motive expert would be recommended. The current copper/graphite material appears to work well for the collector bar.

4) **Conductive Strips**: Continuing use of stainless steel is recommended.

5) **Insulating gaps between strips**: If the gaps are to hold up for longer periods of time new more abrasion resistant materials must be used.

6) **Maintenance**: Vigilance of the road's condition and countermeasures such as scheduled sweeping are recommended.

**Steps to Carry Out Recommendations**

These steps would be recommended in future designs and study:

1. Redesign and install system on a roadway for higher speed higher power testing. Observe the recommendations mentioned in the previous section in the redesign.

2. Test system for an extended period of time under real world roadway conditions.

3. Continue testing redesign on simulator.
Safety Test 2: Endurance Runs
Data Collection Sheet #1

Nick Musachio
Technical Director

Roger Young
SCTC Instrumentation Instructor

Date 28-Feb-95 9:15 AM
Conditions Cold (Low temp -1 F -26 wind chill)
Time per revolution = 19.8 seconds Aprox. 5mph
Stopped @ 69 miles and inspected. All systems functioning

Date 01-Mar-95
Stopped @ 265 miles and inspected. All systems functioning
Time per revolution = 12.04 seconds or 8.5 mph
Low Temp -6 degrees

Date 02-Mar-95
Vehicle stopped itself @ 379 miles.
Cause of stoppage was a melted solder joint on a fused resistor. System failed safe. Failed in "off" position.
Low temp -15 degrees F

Observation: Fusable resistors are used to buffer the low voltage input of the SCR's
These resistors give off heat when the system is functioning. At high speeds the resistors get very hot.
If the heat is too high the solder melts and the wires separate. Thermal management needs to be addressed.
The fusible resistors used in the switching system need to be heat sunk or increased in power.
Safety Test 2: Endurance Runs

Data Collection Sheet #1

Nick Musachio
Technical Director

Roger Young
SCTC Instrumentation Instructor

Date 27-Apr-95 5:00 p.m.
Conditions 45 Degrees F, Cloudy
Time per revolution = 12 seconds Aprox. 8.5 mph
Stopped @ 180 miles. All systems functioning

Date 28-Apr-95 9:20 a.m.
Conditions 55 F, Cloudy 5mph wind
Time per revolution = 14 seconds (7mph)
Visual inspection at 6:00 pm all systems functioning, left running

Date 28-Apr-95
Stopped @ 400 miles and inspected: All systems functioning
Time per revolution = 12.04 seconds or 8.5 mph

Date 29-Apr-95 3:20 p.m.
Visual inspection: all systems running. Mileage approximately 150 miles
Time per revolution = 14.4 seconds

Date 30-Apr-95 5:00 p.m.
Visual inspection: all systems running
Time per revolution = 14 seconds
Temp 50s, windy and cloudy
Safety Test 2: Endurance Runs
Data Collection Sheet #1

Date 30-Apr-95
Stopped @ 530 miles to inspect. System functioning

Date 01-May-95 1:50 p.m.
All systems functioning. System shut down
Miles completed: 532.4
Average speed: 7 mph.

Observation: Fusible resistors are used to buffer the low voltage input of the SCR's
These resistors give off heat when the system is functioning. At high speeds the resistors get very hot.
If the heat is too high the solder melts and the wires separate. Thermal management needs to be addressed.
The fusible resistors used in the switching system need to be heat sunk or increased in power.
Safety Test 2: Endurance Testing

Data Collection Sheet #2 - Wear Data

Observer: Nick Musachio, Technical Director, Roger Young, Instrumentation, SCTC

411 miles of running on 2/28/95-3/2/95
Weather: very cold 20 degrees to -15 degrees F.

<table>
<thead>
<tr>
<th>Pantograph Section</th>
<th>Each Measured Section is 4&quot; long.</th>
<th>Measurements taken at center, rear facing edge.</th>
<th>Net Avg Change</th>
<th>Greatest</th>
</tr>
</thead>
<tbody>
<tr>
<td>Segment#</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Before</td>
<td>6.9</td>
<td>7.4</td>
<td>7</td>
<td>6.5</td>
</tr>
<tr>
<td>After</td>
<td>6.8</td>
<td>6.8</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>net Change</td>
<td>-0.1</td>
<td>-0.6</td>
<td>-1</td>
<td>0.5</td>
</tr>
</tbody>
</table>

| Segment#           | 1      | 2       | 3       | 4       | 5       | 6       | 7       | 8       |
| Before             | 7      | 6.8     | 7.9     | 7.6     | 5.8     | 7.1     | 7.9     |
| After              | 6.9    | 7       | 7.4     | 7.3     | 5.9     | 6.8     | 7       |
| net Change         | -0.1   | -0.2    | -0.5    | -0.3    | -0.1    | -0.3    | 0.9     | -0.09 mm | .9 mm   |

| Segment#           | 1      | 2       | 3       | 4       | 5       | 6       | 7       | 8       |
| Before             | 7.4    | 7.4     | 8       | 7.4     | 6       | 4.5     | 6.8     | 6.8     |
| After              | 6.9    | 6.9     | 7.7     | 7       | 5.5     | 4.6     | 7       | 6.9     |
| net Change         | -0.5   | -0.5    | -0.5    | -0.4    | -0.5    | -0.1    | 0.2     | 0.1     | -0.28 mm | .5 mm   |
E-TRAN ROAD POWERED ELECTRIC VEHICLE
SAFETY TEST 3 REPORT: CORROSION

I. Some Considerations On Possible Corrosive Attacks On The Power Strip
Of The Proposed E-TRAN System

Richard A. Oriani, Ph.D.
Director Emeritus
Corrosion Research Center
Dept. of Chemical Engineering and Materials Science
University of Minnesota
March, 1995

A. INTRODUCTION

The use of a metallic conductor lying upon but insulated from the road bed is problematic from the corrosion point of view. The severity of the problem will depend strongly on the design of the system and on the environmental conditions during operation. The following paragraphs present an overview of the corrosion problems likely to be encountered in the use of 304 stainless steel for the power strip of the E-TRAN system. Corrosion of a metal ordinarily requires contact of the metal by an aqueous solution of ions, and this will certainly take place at least intermittently during operation of the proposed system. The following remarks are based on this premise.

The chief modes of corrosive attack of stainless steels are pitting, crevice corrosion, and intergranular corrosion. These are forms of localized attack which depend upon heterogeneities in the metal and/or in the environment. These are discussed with specific reference to 304 stainless steel.

B. PITTING CORROSION

This form of localized attack initiates where contacting water has ions that raise the electrical potential (corrosion potential) by a redox reaction and where the naturally occurring oxide film on the stainless steel is weakened by virtue of chemical heterogeneities in the metal. Differential aeration of the aqueous layer can also have an initiating action. Once initiated, the pitting can become self-sustaining by the acidification that takes place by the hydrolysis of the metal ions with chloride ions in the water. Sources of deleterious ions that would contact the power strip would be dust particles, atmospheric contaminants such as those brought down by acid rain, and most importantly, de-icing salts. Chloride ions are particularly harmful, the severity increasing with increasing concentration. Even a very dilute solution of chloride ions can be...
harmful as it increases in concentration during drying. A dried-out deposit of a chloride can absorb moisture from air of high relative humidity to become harmful. Copious rainfall would be beneficial by washing away road salts.

Because the use of de-icing salts and the occurrence of dust and caked-on mud are expected during the service life of the power strip, the only pitting mitigation measures that can be taken are those involving the material and the design of the power strip. A more pit-resistant stainless steel such as 316 would be desirable but the additional expense would be a deterrent. To avoid inducing chemical heterogeneity in the 304 stainless steel, welding operations that produce zones with temperatures between 930 and 1560°F should be avoided unless subsequent annealing can be done. Brazing should also be avoided if such temperatures are developed. The reason for the development of chemical heterogeneity in the metal is that the carbon in the steel reacts with the alloying element chromium to form a carbide, thereby depleting the steel matrix of the alloyed chromium. This is called sensitization of the stainless steel. This reaction occurs preferentially at grain boundaries, so that the chromium-depleted regions are mostly along grain boundaries and pitting tendency will be greatest there. Another problem that such an induced heterogeneity can cause is intergranular corrosion, in which the grain boundary metal corrodes away, developing separated particles of metal. The chromium-depletion problem can be avoided by employing a stainless steel that is very low in carbon, such as 304-L.

Design of the power strip and its support structure to decrease pitting should emphasize avoidance of re-entrant angles and crevices that can retain water.

C. CREVICE CORROSION

This is a form of localized corrosion that is very similar in mechanism to pitting, but in which the reason for the initiation is geometrical. A very narrow gap between the stainless steel and some other solid body such as a gasket, caked mud or another metal permits access of water with its dissolved impurities but makes diffusion of oxygen from the air slow and difficult. The result is that the oxygen-deficient portion of the surface of the stainless steel corrodes preferentially because the protective oxide film cannot be maintained there. Local acidification by metal ion hydrolysis occurs, as in pitting corrosion, since the acidity cannot easily diffuse away in the very thin layer of water in the crevice.

Clearly, crevices between the power strip and its support structure must be avoided. But also debonding of an adhesive used between the stainless steel and the support structure would produce very effective harmful crevices. An adhesive system must be developed (if an adhesive
is to be used) that will leave an adherent film on the steel if adhesive failure occurs in service. Oxygen-depleted regions under caked-on dirt will also cause localized corrosion when the deposit becomes wet. To avoid this type of corrosion it may be necessary to develop a brushing apparatus that is periodically run over the power strip to free it of dirt deposits.

D. GALVANIC CORROSION

Contact between dissimilar metal when both are bathed by the same aqueous solution can cause one metal to corrode at a faster rate, and the other metal to be protected from corrosion, than would be the case if the metals were not in contact. This so-called galvanic corrosion effect usually does not deleteriously affect stainless steels themselves, unless they contact metals such as titanium, gold or platinum. However, two notes of caution are advisable. The first one concerns the contacts between current leads, presumably made of copper and the stainless steel power strip. The galvanic corrosion effect between copper and stainless steel is quite variable, i.e. the copper or the steel may corrode more rapidly depending on poorly defined variables. If brazing is the method of making the connection between the copper lead wires and the stainless steel, the possible galvanic interactions among the copper, braze metal, and steel should be considered. These vary considerably depending on the nature of the braze metal. In addition, the brazing operation must not leave crevices between braze and the stainless steel (see the section on crevice corrosion). The writer is aware that the intention is to seal brazed contacts from the environment by suitable bonding agents to maintain the junctions dry. However, one must remember that dynamic mechanical stresses and chemical stresses will permit Murphy’s Law to operate, so that one must design for environmental intrusion.

The second note of caution concerns the interaction between graphite and stainless steel. The current plan is to use graphitic slides to convey electricity from the power strip to the vehicle. Friction between the stainless steel and the slider may cause graphite to be deposited on the steel. The effect of this may be galvanic corrosion of the 304 stainless steel. Whereas at the present time no data on this problem have turned up, it is in principle a possibility and it is known to happen with other metals. The stainless steel covered by the transferred carbon would be protected from corrosion at the expense of areas not touched by the graphitic slider. These areas would corrode, probably by pitting, at a faster rate than without the effect of the transferred carbon whenever a water solution wets the steel. It is recommended that a literature search on this possibility be made and that in the absence of relevant information, an experimental program be undertaken.
E. STRAY CURRENT PROBLEM

Although the intention is to electrically insulate the power strip segments from ground and from each other, it is probable that water with dissolved ions will at times form a conducting path between adjacent segments of opposite polarities. Besides wasting power, a more pernicious problem may be the loss of metal by the power strip segment while that segment is at positive polarity. The corrosion would be concentrated at the ends of the segments.

F. RECOMMENDATIONS

1. Determine whether or not welding or brazing operations that can cause sensitization of the 304 stainless steel will be necessary. If so, 304-L stainless should be considered.

2. Do a literature search for galvanic corrosion between brazing alloys and stainless steel. If information is not found, an experimental program should be undertaken.

3. Same as item 2, for graphite and stainless steel.

4. Develop an experimental program to establish the severity of corrosion caused by stray current, using the proposed power strip segments joined by the proposed insulating segment, all covered by chloride-containing water film, with the proposed potential difference between the power strip segments applied during relevant time durations.

5. Consider designs of the support structure for the power strip that avoid crevices and re-entrant angles.
II. Optical And Electron Microscopy Analysis Of Power Strip For RPEV

Professor David A. Shores, Ph. D.
Corrosion Research Center
Dept. of Chemical Engineering and Materials Science
University of Minnesota
April 25, 1995

SUMMARY

A segment of a 304 stainless steel pipe, which has functioned for several months as a conductor in a RPEV power strip, was examined for evidence of degradation by corrosion and/or wear. The present condition of the pipe was documented by photographing three areas at a magnification of 1.3X and by examining one area in a Scanning Electron Microscope.

There was no apparent evidence of corrosion on the pipe. Although longer exposures may lead to corrosion of the stainless steel tubing outside the wear track, e.g., by pitting, none was seen on the subject sample. The only evidence of degradation was the track caused by the sliding pantograph. Both the wear track and other areas were photographed at low magnification. SEM examination focused primarily on the wear track. Micrographs (35X to 2500X) of the track areas showed where the pantograph had been in contact, causing scratches on “fresh” metal, and some patches, which are below the elevation of the scratched areas where material had been removed by the wear process. In two areas within the patches, we observed small, open cracks. Although I’m not an expert on wear mechanisms, my impression is that the cracks were induced by the wear process, and probably they are part of the process by which material is removed in the patch area. Elemental analysis was carried out by EDS (energy dispersion spectroscopy) within the patches in the wear track, and the results are attached. In addition to high levels of Fe, Cr and Ni from the stainless steel, as expected, low levels of sulfur and chlorine were also found. The origin of the S and Cl is not certain, but probably is from track-side salts and contaminants. It is conceivable that such contaminants may be involved in the material-removal processes causing the patches in the wear track, but further testing would be required to confirm this.

A simple estimate has been made of the average amount of material lost by wear, based on taking the track width as a chord of a circle (see attached sketch and equations). The results are reported as a volume (or mass) of metal removed per meter of pipe length. These estimates do not account for any faster local rate of wear that might be associated with the patches.
The wear volume of stainless steel tube can be calculated from simple geometrical relations. As illustrated in Figure below, for a piece of tube with length L, if one assumes the measured wear track width is w, the tube outer and inner radii are R and r respectively, the wear volume thus can be expressed as

\[
\Delta V = \frac{1}{2} R^2 (\theta - \sin \theta) \cdot L = \left( \frac{1}{2} R^2 \theta - \frac{1}{2} w \sqrt{R^2 - \left(\frac{w}{2}\right)^2} \right) \cdot L
\]

\[
= \left( R^2 \sin^{-1} \left(\frac{w}{2R}\right) - \frac{1}{2} w \sqrt{R^2 - \left(\frac{w}{2}\right)^2} \right) \cdot L \quad \text{(1)}
\]
The wear volume per unit length tube is

$$\Delta v = \frac{\Delta V}{L} = R^2 \sin^{-1}\left(\frac{w}{2R}\right) - \frac{1}{2} w \sqrt{R^2 - \left(\frac{w}{2}\right)^2}$$

(2)

The wear weight loss per unit mass tube can be written as

$$\Delta m = \frac{\left(R^2 \sin^{-1}\left(\frac{w}{2R}\right) - \frac{1}{2} w \sqrt{R^2 - \left(\frac{w}{2}\right)^2}\right) \cdot L \cdot \rho}{\pi(R^2 - r^2) \cdot L \cdot \rho} = \frac{R^2 \sin^{-1}\left(\frac{w}{2R}\right) - \frac{1}{2} w \sqrt{R^2 - \left(\frac{w}{2}\right)^2}}{\pi(R^2 - r^2)}$$

(3)

where $\rho$ is the tube metal density.

For the tube used, $\rho = 8.04 \text{ g/cm}^3$, $R=7.95 \text{ mm}$, $r=6.45 \text{ mm}$, for two ends of the tube, $w_e=2.4 \text{ mm}$, and for middle section of the tube, $w_m=1.1 \text{ mm}$, therefore

$$\Delta v_e = R^2 \sin^{-1}\left(\frac{w_e}{2R}\right) - \frac{1}{2} w_e \sqrt{R^2 - \left(\frac{w_e}{2}\right)^2}$$

$$= 7.95^2 \times \sin^{-1}\left(\frac{2.4}{2 \times 7.95}\right) - \frac{1}{2} \times 2.4 \times \sqrt{7.95^2 - \left(\frac{2.4}{2}\right)^2} \approx 0.1459 \text{ cm}^3 / \text{m} \cdot \text{tube}$$

$$= 1.1730 \text{ g/l} - \text{tube}$$

$$\Delta v_m = R^2 \sin^{-1}\left(\frac{w_m}{2R}\right) - \frac{1}{2} w_m \sqrt{R^2 - \left(\frac{w_m}{2}\right)^2}$$

$$= 7.95^2 \times \sin^{-1}\left(\frac{1.1}{2 \times 7.95}\right) - \frac{1}{2} \times 1.1 \times \sqrt{7.95^2 - \left(\frac{1.1}{2}\right)^2} \approx 0.0140 \text{ cm}^3 / \text{m} \cdot \text{tube}$$

$$= 0.1126 \text{ g/l} - \text{tube}$$
\[ \Delta m_e = \frac{R^2 \sin^{-1}\left(\frac{w_e}{2R}\right) - \frac{1}{2}w_e \sqrt{R^2 - \left(\frac{w_e}{2}\right)^2}}{\pi(R^2 - r^2)} \]

\[ 7.95^2 \times \sin^{-1}\left(\frac{2.4}{2 \times 7.95}\right) - \frac{1}{2} \times 2.4 \times \sqrt{7.95^2 - \left(\frac{2.4}{2}\right)^2} \approx 2.150 \times 10^{-3} \text{ g/g-tube} \]

\[ \Delta m_m = \frac{R^2 \sin^{-1}\left(\frac{w_m}{2R}\right) - \frac{1}{2}w_m \sqrt{R^2 - \left(\frac{w_m}{2}\right)^2}}{\pi(R^2 - r^2)} \]

\[ 7.95^2 \times \sin^{-1}\left(\frac{1.1}{2 \times 7.95}\right) - \frac{1}{2} \times 1.1 \times \sqrt{7.95^2 - \left(\frac{1.1}{2}\right)^2} \approx 2.059 \times 10^{-4} \text{ g/g-tube} \]

### Table: Wear Evaluation

<table>
<thead>
<tr>
<th></th>
<th>Tube ends</th>
<th>Tube middle part</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>cm³/m-tube</td>
<td>g/m-tube</td>
</tr>
<tr>
<td></td>
<td>cm³/m-tube</td>
<td>g/g-tube</td>
</tr>
<tr>
<td>Tube ends</td>
<td>0.1459</td>
<td>1.1730</td>
</tr>
<tr>
<td>2.150x10⁻³</td>
<td>0.0140</td>
<td>0.1126</td>
</tr>
<tr>
<td>Tube middle part</td>
<td>2.059x10⁻⁴</td>
<td></td>
</tr>
</tbody>
</table>
E-TRAN ROAD POWERED ELECTRIC VEHICLE
SAFETY TEST 4 REPORT

EEA PROJECT NO. 3843
APRIL 5, 1995
WILLIAM F. THIESSE, PE

1.0 INTRODUCTION

1.1 Sparking (arcing) has been observed between the pantographs and the electric rail. This observation prompted concern that the E-TRAN vehicles may be a source of radio frequency interference (RFI) which is associated with electric arcing. RFI consists of unintended electromagnetic signals which interfere with desired signals such as radio and television broadcasts.

1.2 This test was designed to measure the strength of the electromagnetic energy radiated from the vehicle as it operates.

1.3 Test 4 was intended to measure the increase of RFI radiated by the test vehicle compared to the usual RFI levels naturally occurring in the vicinity of the test. The test observed radiation levels across specific bands of frequencies and at specific frequencies.
2.0 THE TEST

2.1 The receiving antenna was set up 6 feet from the E-TRAN simulator at the St. Cloud Technical College. Base measurements were recorded without the vehicle operating. After the base measurements were recorded, the vehicle was put into operation and the measurements were taken again. The recorded measurements consist of:

1. Center frequency
2. Band width
3. Base amplitude
4. Test amplitude

2.1.1 Center frequency is the middle frequency of the band of frequencies being measured. See example of Figure 4-1.

2.1.2 Base amplitude is the average strength (amplitude) of the radiated signals at the different frequencies within the measured bandwidth without the vehicle operating.

2.1.3 Test amplitude is the average strength of radiated signals with the vehicle operating.

2.1.4 Band width is the range of frequencies being measured.

2.2 Amplitude measurements were recorded in dBm. This is a logarithmic system with a signal strength of 1.0 mWatt equal to 0 dBm. Each 3 dBm increase in measured value transforms to a doubling of signal strength. For example, an increase from 2 dBm to 11 dBm is an increase of 9 dBm. 11 - 2 = 9. 9 dBm translates to three individual 3 dBm increases. 3 dBm + 3 dBm + 3 dBm = 9 dBm. Thus the signal strength has doubled 3 times. 2 x 2 x 2 = 8. The increase of 9 dBm translates into a signal that is 8 times stronger than the original signal.
FIGURE 4-1
Likewise, a decrease of 3 dBm represents a halving of signal strength. A signal value of -51 dBm means the signal has been halved seventeen times. $51 \div 3 = 17$. For the mathematicians, $2^{-17} = 7.6 \times 10^{-6}$. For the non-mathematicians, the signal strength is over 100,000 times smaller than the reference signal. Since the reference in dBm is 1.0 mW, our measurements of RFI amplitude were typically in the nanoWatt range. The prefix nano- means billionth.

2.3 Amplitude measurements were recorded for 20 separate frequency bands ranging from 20 kHz to 60 MHz. The test amplitude recorded was the maximum value observed at the particular band width and center frequency. This maximum always occurred as the vehicle passed closest to the antenna (6 feet). When the vehicle passed the point farthest from the antenna (approximately 50 feet), the minimum amplitude was observed.

2.4 The recorded measurements are shown in Figures 4-2, 4-3, and 4-4.

3.0 THE RESULTS

3.1 The measurements indicate that there is measurable electromagnetic radiation from the vehicle in operation. The maximum measured amplitude was -43 dBm which transforms to $49.6 \times 10^{-9}$ Watts. This is a very small number. This maximum occurs in two areas of the measured frequencies, around 20 kHz and again between 400 kHz and 800 kHz. The maximum at 20 kHz is probably due to radiation from the electric motor drive on the vehicle. The maximum between 400 kHz and 800 kHz is probably due to the arcing between the pantographs and the rail.
4.0 CONCLUSIONS

4.1 Federal Communications Commission (FCC) Rules

4.1.1 Rules concerning RFI are covered in Title 47 Code of Federal Regulations Part 15. The E-TRAN system falls under the definition of an incidental radiator. An incidental radiator is a "Device that generates radio frequency energy during the course of its operation although the device is not intentionally designed to generate or emit radio frequency energy."

4.1.2 Section 15.13 of Title 47 CFR states: "Manufacturers of these devices (incidental radiators) shall employ good engineering practices to minimize the risk of harmful interference." There are no other specific FCC regulations which apply to the E-TRAN system.

4.1.3 Although there are no specific requirements for incidental radiators, there are requirements for a different class of devices known as "unintentional radiators". The E-TRAN system emitted electromagnetic radiation measured during this test falls below the FCC maximums for unintentional radiators.

4.2 Radiated electromagnetic energy from the vehicle in operation is negligible. The amplitude maxima observed at 20 kHz and between 400 kHz and 800 kHz were expected. A maximum around 20 kHz was expected because these are the frequencies radiated by the motor drive. A maximum around 400 to 800 kHz was expected because these frequencies are characteristic of radiated energy from electric arcs. The radiated energy poses no foreseen interference problems. No further investigation is recommended.
## E-TRAN Road Powered Electric Vehicle Safety Test 4 Data Collection Sheet

<table>
<thead>
<tr>
<th>Center Frequency</th>
<th>Base Amplitude</th>
<th>Test Amplitude</th>
<th>Bandwidth</th>
<th>Reference Base</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>20KHz</td>
<td>-50dBm</td>
<td>-43dBm</td>
<td>40KHz</td>
<td>-10dBm</td>
<td>Test amplitude was the maximum measured which was invariably observed as the vehicle passed closest to the antenna. Relative amplitudes observed when the vehicle was farthest from the antenna were near the base measurement.</td>
</tr>
<tr>
<td>40KHz</td>
<td>-42dBm</td>
<td>-45dBm</td>
<td>40KHz</td>
<td>-10dBm</td>
<td>Base amplitude measurement was recorded with the vehicle turned off.</td>
</tr>
<tr>
<td>60KHz</td>
<td>-46dBm</td>
<td>-50dBm</td>
<td>40KHz</td>
<td>-10dBm</td>
<td></td>
</tr>
<tr>
<td>80KHz</td>
<td>-54dBm</td>
<td>-50dBm</td>
<td>40KHz</td>
<td>-10dBm</td>
<td></td>
</tr>
<tr>
<td>100KHz</td>
<td>-52dBm</td>
<td>-56dBm</td>
<td>40KHz</td>
<td>-10dBm</td>
<td></td>
</tr>
<tr>
<td>200KHz</td>
<td>-54dBm</td>
<td>-56dBm</td>
<td>200KHz</td>
<td>-10dBm</td>
<td></td>
</tr>
<tr>
<td>400KHz</td>
<td>-48dBm</td>
<td>-43dBm</td>
<td>200KHz</td>
<td>-10dBm</td>
<td></td>
</tr>
</tbody>
</table>

Test Equipment: Hewlett Packard 8539E Spectrum Analyzer
A H Systems Active Monopole Antenna 60MHz

Date: 3-23-95
Time: 1:30PM
Location: St Cloud Technical College
Recorder: Bill Thiesse
Position: Consulting Electrical Engineer

Comment - Test amplitude was the maximum measured which was invariably observed as the vehicle passed closest to the antenna. Relative amplitudes observed when the vehicle was farthest from the antenna were near the base measurement.
<table>
<thead>
<tr>
<th>Center Frequency</th>
<th>Base Amplitude</th>
<th>Test Amplitude</th>
<th>Bandwidth</th>
<th>Reference Base</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>600KHz</td>
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<td>800KHz</td>
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<td>200KHz</td>
<td>-10dBm</td>
<td></td>
</tr>
<tr>
<td>1MHz</td>
<td>-51dBm</td>
<td>-49dBm</td>
<td>200KHz</td>
<td>-10dBm</td>
<td></td>
</tr>
<tr>
<td>2MHz</td>
<td>-58dBm</td>
<td>-48dBm</td>
<td>2MHz</td>
<td>-10dBm</td>
<td></td>
</tr>
<tr>
<td>4MHz</td>
<td>-50dBm</td>
<td>-47dBm</td>
<td>2MHz</td>
<td>-10dBm</td>
<td></td>
</tr>
<tr>
<td>6MHz</td>
<td>-57dBm</td>
<td>-51dBm</td>
<td>2MHz</td>
<td>-10dBm</td>
<td></td>
</tr>
<tr>
<td>8MHz</td>
<td>-52dBm</td>
<td>-53dBm</td>
<td>2MHz</td>
<td>-10dBm</td>
<td></td>
</tr>
</tbody>
</table>

Figure 4-3
<table>
<thead>
<tr>
<th>Center Frequency</th>
<th>Base Amplitude</th>
<th>Test Amplitude</th>
<th>Bandwidth</th>
<th>Reference Base</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>10MHz</td>
<td>-77dBm</td>
<td>-52dBm</td>
<td>2MHz</td>
<td>-10dBm</td>
<td></td>
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<td>20MHz</td>
<td>-75dBm</td>
<td>-55dBm</td>
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<td>30MHz</td>
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<td>20MHz</td>
<td>-10dBm</td>
<td></td>
</tr>
<tr>
<td>50MHz</td>
<td>-85dBm</td>
<td>-71dBm</td>
<td>20MHz</td>
<td>-10dBm</td>
<td></td>
</tr>
<tr>
<td>60MHz</td>
<td>-73dBm</td>
<td>-73dBm</td>
<td>20MHz</td>
<td>-10dBm</td>
<td></td>
</tr>
</tbody>
</table>

A H Systems Active Monopole Antenna 60MHz

Figure 4-4
1.0 FACTORS CONTRIBUTING TO HUMAN INJURY FROM ELECTRIC SHOCK

A person will receive an electric shock if that person becomes part of a conducting path (circuit) between two opposite poles of the rail system. See figure 1. The severity of the shock is dependent on several factors:

1. System voltage.
2. Length of time the person is in the circuit.
3. Impedances of the different components of the circuit.

1.1 SYSTEM VOLTAGE

Voltage is a measure of the electric force that drives electric current through a conducting medium such as a copper wire or in this discussion a human body. It is the electric current that injures humans. If the voltage is low, say below 50 volts, the chances for injury from electric shock are reduced. This is because there is less electric force and therefore less electric current. If the voltage is higher, say 300 volts, the chance for injury from electric shock is increased because there is sufficient electric force to drive larger currents through a human body. The simulator being tested uses 330V DC at the rail segments.

1.2 LENGTH OF TIME THE PERSON IS IN THE CIRCUIT

Injury from electric shock is not instantaneous. The longer a body is in the electric circuit, the more risk there is to the victim. A current of 100 milliamperes for 3 seconds is equivalent to a current of 900 milliamperes for 0.03 seconds in causing fibrillation. [1]
Figure 5-1
1.3 IMPEDANCES OF THE DIFFERENT COMPONENTS OF THE CIRCUIT

Impedance is a measure of the limiting effect that different materials have on the electric circuit. For example, a person standing on two electric rails will be more susceptible to electric shock if they are barefoot than they would be wearing rubber soled shoes (see Figure 5-1). This is because the rubber raises the impedance of the electric circuit. The current limiting effect of the rubber reduces the electric current increasing protection to the wearer.

2.0 DESIGN SAFETY FEATURES

Two features are included in the system design to reduce the risk that a person will become part of the electric circuit.

1. Automatic rail switching.
2. Electrically ungrounded system.

2.1 AUTOMATIC RAIL SWITCHING

The system is designed to energize (turn on) the electric rails only when sensors sense an oncoming vehicle. If no vehicle is present, the rails are de-energized (turned off).

2.2 ELECTRICALLY UNGROUNDED SYSTEM

The electrical system including the electric rail segments are purposely isolated from the earth (ground). This excludes surfaces in contact with the earth such as pavement from becoming part of the electrical circuit under normal conditions. The purpose of not grounding the electrical system is that this allows a person to touch one pole (positive or negative rail segment) without completing the electric circuit.
3.0 FACTORS WHICH MIGHT DEFEAT SAFETY DESIGN FEATURES

There is no risk of electrical shock when the rails are turned off. There is no risk of electrical shock when a person contacts a single rail segment and the system is effectively ungrounded. Electrical shock requires simultaneously:

1. A rail segment is energized (turned on).
2. A human is in electrical contact with the system.
3. The human contact completes an electric circuit.

Three examples of how these might occur simultaneously follow. These examples are representative and not intended to be exhaustive. No attempt is made to quantify risk.

3.1 STOPPED VEHICLE

Rail segments are energized in the presence of a vehicle. If the vehicle is stopped and the energized rail segments are longer than the vehicle, energized rail could be exposed to pedestrians. A person contacting two rail segments of opposite polarity could receive a shock depending on variable parameters listed in paragraph 1.0.

3.2 UNINTENTIONAL GROUNDING

Assume the same scenario as in 3.1 above except that now the system is unintentionally grounded by having a puddle of saltwater slush provide electrical contact between one rail segment and the concrete pavement. Under these conditions, a person could receive an electrical shock by contacting the wet pavement and the rail of opposite polarity subject to the parameters of paragraph 1.0.

3.3 SYSTEM FAILURE

If a switch fails closed, the rails could remain energized without a vehicle present. Persons coming in contact with two energized rails of opposite polarity as in paragraph 3.1 or a single oppositely polarized rail and pavement when the system is unintentionally grounded as in paragraph 3.2 could receive an electrical shock subject to the conditions of 1.0.
4.0 CONCLUSION

The potential for electric shock to humans exists with the system in its present state of design. For instance, the idea that the power system will remain ungrounded given Minnesota's weather is not well founded. This was demonstrated in Safety Test 1C.

Quantification of risk is complicated because of the large number of different ways in which humans could come in contact with the system. A study providing a comprehensive quantification of risk is beyond the capabilities of the present research budget. However, risk factors were considered heuristically by a discussion group formed for that task. Suggested design improvements which should reduce risk to pedestrians are included in the report attached to this report in Appendix A.

5.0 BIBLIOGRAPHY

1.0 INTRODUCTION

1.1 Appendix A is the report from a discussion group that analyzed the E-TRAN system from the perspective of pedestrian safety. The basic question for analysis was "What could a pedestrian do to get shocked?"

1.2 The discussion group was made up of a subcommittee of the Safety Training and Technology Evaluation Group. The discussion took place on April 17, 1995 at the conference room located at the MNDOT office in Albertville, MN. Attendees were:

David Johnson PE - MNDOT Office of Research Admin
John Palmer PhD - SCSU
Nick Musachio - E-TRAN
William Thiesse PE - EEA

1.3 Although the original intent of the discussion was to evaluate E-TRAN system safety, the group soon discovered that the system designers had concentrated up to this point on making the system operational. Very little safety system design had been accomplished. The group acknowledged this fact and decided to hypothesize an E-TRAN system with desirable safety systems.
2.0 THE DISCUSSION

2.1 The group adopted as its basic premise: "A pedestrian is at risk if the track is energized."

2.2 Three possible components of system safety were identified:

1. Basic system design
2. Automatic shutoff systems
3. Manual shutoff activated by the vehicle driver.

2.2.1 Basic System Design. The system should be designed to sense oncoming vehicles and turn the track on at the appropriate time. Two signals should be necessary for sensing oncoming vehicles.

1. Vehicle proximity sensor such as a magnetic loop detector.
2. Vehicle identifier sensor which identifies a vehicle as authorized to access the system via a coded radio signal.

2.2.1.1 This two-signal approach would reduce the probability that the system will be triggered falsely. Unauthorized triggering of the switches would require duplication of the coded radio signal and the presence of a vehicle. This sort of safety system failure is unlikely.

2.2.2 Automatic Shutoff Systems. Switch failure is more likely to occur than false triggering. Two kinds of switches are being considered by the system designer:

1. Static switches (SCR)
2. Electro-magnetic switches

In either case, failure of the switch in the closed (on) position would leave the electrified rail energized. SCRs can remain in conduction (on) if the controlled current does not achieve a sufficient zero crossing. Thus, the use of SCRs as switches will require alternating current or pulsed direct current to enable the SCRs to turn off.
Switch failure is a real possibility that must be taken into account. Monitoring circuits should be designed to sense voltage on the rail. If voltage is sensed when the switch is supposed to be open (off), the switch can be assumed to have failed and a second switch can be employed to turn off the system.

Thus, two levels of switching were identified:

1. Primary switch - controlled by vehicle sensing.
2. Secondary switch - controlled by monitoring circuits.

2.2.2.1 Secondary switches should be controlled from at least two sources:

1. Primary switch monitoring circuits
2. Vehicle speed transmitter

The primary switch monitoring circuits were mentioned in the previous paragraph. More monitoring circuits beside the simple voltage sensing mentioned are possible. Such circuits are difficult to define until the system design begins to mature.

The vehicle speed transmitter arose from a discussion of the possibility of a stopped vehicle on the system. The system design as presently envisioned includes switched rail segments physically longer than the vehicle. A stopped, authorized vehicle would cause switched rail segments to remain on when pedestrians could be present. It was supposed that pedestrians would be unlikely to be close to the rail segments in the presence of an oncoming vehicle above a certain speed because they would be cautious of the moving vehicle. A slowly moving or stopped vehicle negates this supposition. A signal from the vehicle indicating it is moving faster than a threshold speed should be included in the design. If the vehicle speed falls below the threshold, the signal to the secondary switch stops and the switch opens (turns off).

2.2.3 Manual Shutoff Activated By the Vehicle Driver. The group discussed and agreed that since pedestrian safety was of primary importance, the driver manual shutdown should control the entire system. This suggested a third or tertiary switch. The tertiary switch would be considered the last line of defense to be used when the driver is unsure that the system is safe.
2.2.3.1 Having this switch at the disposal of the driver would give the driver added responsibility. Training of the drivers in the identification of abnormal conditions and the use of the switch will be necessary. For example, circumstances requiring the driver to use the manual shutdown include:

- Gasoline spills
- Unusual appearance in power strip
- Pedestrian in vicinity of the strip
- Pedestrian on the strip
- Foreign object on the strip

2.2.3.2 Automatic system monitoring could signal the driver that the system condition is abnormal. The driver could be alerted with a visual and audible alarm to be aware of a condition or to activate the manual shutdown directly.

2.2.4 As a further precaution, the subcommittee suggests that the rail segments not be used continuously. The system route should be analyzed and rail segments should be omitted from areas of higher pedestrian activity. Safety test 1A demonstrated that the onboard battery can power a vehicle in the absence of electrified rail.

3.0 CONCLUSION

3.1 The subcommittee concluded that a system designed with the provisions described above should be risk tolerant.

3.2 Future analysis of risk should consist of the following components:

1. Define system design completely.
2. Analyze each component individually for risk of failure.
3. Analyze the total risk that the system will fail with the strip energized.
4. Assume that if the strip is energized indefinitely, someone will get shocked.

3.3 Figure 5A-1 summarizes graphically the suggested components for improved system safety.

3.4 Figure 5A-2 shows a simplified switching diagram illustrating relative system placement of primary, secondary, and tertiary switches.
Figure 5A-2
E-TRAN ROAD POWERED ELECTRIC VEHICLE
SAFETY TEST 6 REPORT
Human and Vehicle Factors

MAY 1995
JOHN PALMER, Ph.D.

I. INTRODUCTION

This study was conducted as part of a larger study of the feasibility of the electric vehicle technology known as E-Tran. The Minnesota Legislature provided funds to the Minnesota Department of Transportation to evaluate the feasibility of road powered electric vehicle technology. The St. Cloud Metropolitan Transit Commission serves as fiscal agent for the larger study and has subcontracted with St. Cloud State University to conduct safety evaluations described in the larger study’s evaluation plan under the heading Safety Test 6, Human and Vehicle Factors.

The specific objectives of the Human and Vehicle Factors study are to:

- observe and test human behavior when the power strip is present on a roadway,
- develop and test warning protocols and risk reduction strategies for the presence of the power strip,
- observe and test bicycle, motorcycle, and roller blade interaction with the power strip,
- assess the impact of the power strip on driver behavior,
- assess the impact on automobile performance with regard to steering and braking.

Several types of analysis have been undertaken as part of the series of tests conducted within this study. The analysis can be grouped in two categories: responses to the presence of the power strip and impact of the power strip on vehicle performance.

Assessing the response to the presence of the power strip was accomplished by placing an unpowered power strip on a portion of the roadway used by the Husky Shuttle and then recording the incidence of specific human behaviors associated with the strip. As part of this experiment an effort was made to assess the public reaction to the power strip by keeping a record of the inquiries and complaints received.
A series of experiments conducted at the Minnesota Highway Safety Center were used to determine the impact of the power strip on the handling characteristics of selected highway users. The experiments focused on the impact on likely driver behaviors which occur when the power strip is present on the roadway.

Video taping supplemented observation reporting sheets as a means of collecting data for the two categories of tests. Both descriptive and experimental statistical procedures were used to address the research questions under investigation.

The hypothesis to be tested with respect to responses to the power strip is:

No significant differences in the behavior of drivers and pedestrians traveling a section of the Husky Shuttle will occur when the E-Tran powerstrip is placed on the road. (alpha level at .1)

A case study methodology was used to document the impact of the power strip on vehicle performance.

II. RESPONSES TO THE PRESENCE OF THE POWER STRIP.

After baseline data was collected, an unpowered power strip was placed on the section of the Husky Shuttle immediately to the west of the overhead pedestrian walkway which connects Brown Hall and the Math Science buildings on the campus of St. Cloud State University. The overhead pedestrian walkway served as an excellent location from which observations of pedestrian and vehicle actions were made.

Two weeks prior to the placement of the power strip the techniques for recording data were tested. The techniques included use of a television camera supplemented by observations made by the data collection technician. The purpose of the pilot test was to determine the field of view the television camera provided and the need for supplemental observations made by the data collection technician. The television camera was able to provide all the visual information necessary to address the objectives of the study.

Baseline data was collected from 7:45 AM until 2:15 PM on Monday, Wednesday, and Thursday.
during the week prior (February 6 - 8th, 1995) to the placement of the power strip. Observations of pedestrian and vehicle actions were recorded on video tape. A news release announcing the placement of the power strip was distributed to the St. Cloud area news media on the Thursday afternoon (February 9th, 1995) before the weekend when the power strip was placed. Contact was made with the offices of Public Safety and Public Relations. These offices were asked to record inquiries with regard to the powerstrip's presence on the roadway. The power strip was placed on the roadway late in the day on Sunday. The powerstrip had warning messages spray painted in bright red every few feet. The warning message used the symbol for electric shock and the words "Danger-High Voltage Do Not Step On " (see Figure 6-1 in the appendix).

Data collection began at 7:45 on Monday and ended at 2:15 PM on Monday. Late in the day on Tuesday warning signs were placed at strategic locations along the sides of the street. Data collection was scheduled to resume at 7:45 on Wednesday, but unfortunately a St. Cloud State University snowplow removed the power strip from the roadway sometime late Tuesday or early in the morning Wednesday. This unexpected event cut data collection short, but fortunately there was a large enough number of observations made on Monday to permit testing the hypothesis of the study.

The possibility of snow removal damaging the powerstrip had been taken into consideration. The St. Cloud Public Works department had been informed that the power strip would be placed on the roadway and the snow plow driver who had responsibility for snow removal on that section of roadway had been shown how to avoid the powerstrip. What had not been anticipated was the possibility that other snow plows would be operating on the roadway that included the powerstrip.

Following the completion of the collection of video taped observations of behavior a data collection technician reviewed the video tapes to record in detail the behaviors of direct interest to this investigation. Once all the tapes had been reviewed and the observations coded and entered into a computer file for analysis of data using descriptive and appropriate inferential statistics was completed. The results of this analysis are reported in the next few paragraphs.

A total of 798 pedestrians were observed crossing the street on the Monday used as the baseline. Of the 798 pedestrians observed, 186 crossed the street outside of a crosswalk and 37 were observed crossing the street in very close proximity of the Husky Shuttle bus.
A total of 123 vehicles (116 motor vehicles and 17 bicycles) were observed making lateral movements during the Monday baseline. The general pattern of lateral movement of the vehicles using the roadway was recorded. This pattern involved pulling to the curb, pulling into traffic and passing a parked vehicle. Each of these movements would result in crossing the powerstrip if the strip had been present.

A total of 874 pedestrians were observed crossing the street on the Monday when the powerstrip was present. Of the 874 pedestrians 184 crossed outside of a crosswalk and 25 crossed close to the bus.

A total of 158 vehicles (139 motor vehicle and 19 bicycles) were observed making lateral movements on the Monday when the powerstrip was present. When the general pattern of lateral movement of the vehicles using the roadway when the powerstrip is present is compared to the baseline vehicle movement data a total of 72 vehicle movements directly attributable to the presence of the power strip were observed. These movements fell into two categories: drivers who avoided the powerstrip by moving to the center of the roadway and drivers who avoided the powerstrip by traveling on the extreme right hand side of the lane. With over half of the drivers taking action to avoid the powerstrip, it is clear the presence of the powerstrip changes the behavior of motorists. In the case of drivers moving into the center of the roadway to avoid the powerstrip the potential for an increase in the probability of head-on collisions needs further investigation.

A chi square analysis was completed to determine if there was a significant difference in the proportion of pedestrians crossing outside of a crosswalk with and without the powerstrip being present on the roadway. This analysis found no significant difference in the proportion of pedestrians crossing outside of a crosswalk with and without the powerstrip being present (see table 1).

The presence of the powerstrip did not serve to deter crossing outside of a crosswalk. Pedestrian behavior was unaffected by the presence of the powerstrip on the roadway. Of the 184 pedestrians who crossed outside of the crosswalk when the powerstrip was on the roadway 83 (45%) stepped on the powerstrip on their way across the street. Pedestrians did not try to avoid coming in contact with the powerstrip.
### Table 1

**Pedestrian Crossings With and Without Power Strip**

<table>
<thead>
<tr>
<th></th>
<th>Without Powerstrip</th>
<th>With Powerstrip</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>In Crosswalk</td>
<td>612</td>
<td>690</td>
<td>1302</td>
</tr>
<tr>
<td>Expected</td>
<td>621</td>
<td>680</td>
<td></td>
</tr>
<tr>
<td>Out of Crosswalk</td>
<td>186</td>
<td>184</td>
<td>370</td>
</tr>
<tr>
<td>Expected</td>
<td>176</td>
<td>193</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>798</td>
<td>874</td>
<td>1672</td>
</tr>
</tbody>
</table>

Chi Square 1.232 with 1 DF  No significant difference

The pedestrians’ lack of concern that the powerstrip was present parallels the lack of concern shown by the general public. The news release generated only one inquiry and neither Public Safety or Public Relations received any inquiries. Other than the effort to avoid the powerstrip exhibited by about half of the drivers the best way to describe the public’s response to the powerstrip is apathetic. The short term response of the public should not be generalized to the public’s response to the powerstrip over an extended period of time. Pedestrians showed little concern for their safety with regard to the powerstrip even though the strip prominently displayed a warning message. The warning signs which were placed in prominent locations along the roadway did not create any measurable response. The reality of the apathetic response means that the fail-safe features of the powerstrip will be the best protection against electric shock. The results of this test indicate that people will touch the powerstrip and a significant number (25 out 184) of people will come in contact with the power strip when they are in close proximity to the bus.

### III. IMPACT OF THE POWER STRIP ON VEHICLE PERFORMANCE.

A one hundred foot length of power strip was placed on a roadway at the Minnesota Highway Safety Center and a series of tests were conducted to determine the impact of the strip on vehicle performance and handling. Highway user classifications to be tested included a full size automobile, a motorcycle, a touring bicycle, a mountain bicycle, and roller blades. The power strip was placed in the middle of the lane of a crowned asphalt roadway. The section of roadway used for these tests was straight. The tests involving a motorcycle were canceled because the test strip was damaged beyond repair following the automobile braking tests and the findings with regard to
lane changes show that with bigger tires and faster speeds the powerstrip is an easier obstacle to negotiate.

Tests were conducted to determine the impact of the strip on lane changes which cause the tires of the highway user to cross the power strip at an angle of 5, 15, 45, and 60 degrees. Lane changes for the automobile were conducted at 10, 15, 30, and 40 miles per hour. Lane changes for all other highway user groups were conducted at 5, 10, and 15 miles per hour. A second set of tests were conducted to determine the effect on braking when the tires of the highway user are directly on top of the power strip. The braking tests were conducted at speeds of 2, 5, 10, 15, 20, 25, 30, 35 and 40 miles per hour. It was determined that braking tests for two wheeled vehicles was too dangerous to conduct because of the inherent instability of two wheeled vehicles and the slipperiness of the powerstrip. The tests were recorded on video tape with audio comment provided by the principal investigator.

A. Lane Changing Tests

The first lane change tests were conducted using a mountain bike. The mountain bike had high bred tires designed for off road and on road use. The tires were inflated to the recommended tire pressure. Since the mountain bike did not have a speedometer, the touring bike with a speedometer served as a pace setter for the mountain bike. To achieve the appropriate angle of crossing, the mountain bike rider was instructed to ride parallel to the powerstrip at varying distances from the powerstrip.

The rider was instructed to stay 6" from the powerstrip and then drift across the strip to produce the shallow angle of crossing (2 degrees). To achieve a wider angle of crossing (15 degrees) the rider was instructed to ride parallel to the powerstrip equal distance from the edge of the pavement and the power strip (4'6") and then turn sharply to cross the powerstrip. The widest angle of crossing (45 degrees) was achieved by having the rider ride parallel to the powerstrip at the edge of the roadway (9") and then turn sharply to cross the powerstrip. Each of the angles of crossing were tested beginning at 5 miles per hour and increasing in 5 mile per hour increments until a top speed of 15 miles per hour was attained. Test riders were instructed to roll across the powerstrip rather than try to jump the powerstrip.
The mountain bike rider reported that the powerstrip did not cause any instability in any of the crossings. The rider also reported that it was easier to cross the powerstrip at higher speeds than at lower speeds and it was easier to cross the powerstrip at sharper angles rather than a shallow angle. The width of the roadway available for the test did not accommodate crossing the powerstrip at a 60 degree angle, but the findings at shallower angles clearly show that the powerstrip is easier to cross at sharper angles rather than shallow angles.

The touring bike used to conduct lane changing tests had 1" high pressure tires which were inflated to the maximum rating on the sidewall of the tire. Since the touring bike had a speedometer it was not necessary to have a second rider pace the rider of the touring bike. An identical protocol for determining angle of crossing was employed for the touring bike tests and in the mountain bike tests. The rider of the touring bike reported that at low speed (5 MPH) and a shallow angle (2 degrees) an inexperienced rider may have difficulty maintaining control. The experienced test rider did not have difficulty maintaining control in the low speed test. The touring bike rider reported that with increased speed crossing the powerstrip became easier. The rider also noted that the sharper the angle of crossing the easier the crossing.

The roller blades used to test the powerstrips impact on lane changes had four two inch wheels. The roller blader was instructed to coast across the powerstrip and not attempt to jump the powerstrip. This procedure would not be the preferred means of crossing the powerstrip when roller blading. The preferred method would have the roller blader step over or jump the strip. These tests were designed to test a worst case scenario. An identical protocol for determining angle of crossing was employed for the touring bike, the mountain bike tests, and roller blade tests.

The roller blader reported no difficulty in crossing the powerstrip at a shallow angle (2 degrees) at all of the tested speeds. At a sharper angle (15 degrees) and at higher speed (15 MPH) rolling over the powerstrip caused the blader to lose their balance. The potential for the powerstrip to trip the blader increased with speed and angle of crossing. At the sharpest angle tested (60 degrees) the rolling over the powerstrip caused the blader to lose their balance at low (5 MPH) and moderate (10 MPH) speeds. The 15 MPH test was canceled because it was apparent the blader would fall when rolling over the powerstrip at a 60 degree angle. The powerstrip has the potential to cause a roller blader to fall if the blader does not take action to step over or jump over the powerstrip.
Tests involving a **motorcycle** were scheduled to follow tests involving a full size automobile but since the braking test damaged the test strip beyond simple and timely repair the motorcycle tests were canceled.

A full size vehicle was used to conduct the lane change tests for **automobiles**. The vehicle was equipped with police suspension and properly inflated high performance tires. Each of the lane change tests involving an automobile start with all four tires to the right of the powerstrip. Steering input varied based on the targeted angle of crossing. The width of the roadway available for the test did not accommodate crossing the powerstrip at a 60 degree angle, but tests were conducted at 5, 15, and 45 degrees. The steering input for the crossing at 5 degrees was determined by using one hand steering and moving the steering wheel the width of the driver's hand to the left. The 15 degree angle of crossing was achieved by turning the steering wheel 45 degrees and the 45 degree angle of crossing was achieved by turning the steering wheel 90 degrees. Each angle of crossing was assessed at 10, 15, 30, and 40 miles per hour.

The powerstrip did not adversely affect the lane changes made at all angles of crossing and at all speeds. At higher speeds it was almost impossible to tell that the strip was present.

**B. Braking Tests**

The braking tests were conducted at speeds of 5, 10, 15, 20, 25, 30, 35 and 40 miles per hour. It was determined that braking tests for two wheeled vehicles was to dangerous to conduct because of the inherent instability of two wheeled vehicles and the slipperiness of the powerstrip. These tests were conducted to determine the effect on braking when the tires of the highway user are directly on top of the power strip. For comparison purposes several braking tests were conducted with the tires not on the powerstrip and with and without the anti-lock braking system activated. Braking tests with the anti-lock system operational were conducted at 5, 10, 15, 20, 25, 30, 35 and 40 miles per hour. Braking tests at 30, 35 and 40 miles per hour were conducted with the anti-lock system inoperative.

With the left front and left rear tires riding on top of the power strip a series of quick stops were made. The goal of each quick stop was to bring the vehicle to as quick a stop as possible without
engaging the anti-lock braking system. The only quick stop attempted with the anti-lock brake system activated which did not result in the system becoming engaged was the stop made from 5 miles per hour. The test driver is skilled at using the threshold method of braking but could not avoid engaging the anti-lock braking system at speeds above 5 miles per hour.

Each quick stop with the anti-lock system activated and engaged resulted in straight stops without any skidding. For comparison purposes the anti-lock braking system was deactivated by removing the fuse which protects the electrical circuits for the anti-lock braking system. With the left two tires on top of the powerstrip quick stops were made at 5, 10, 15, 20, 25, and 30 miles per hour. In each case above 5 miles per hour the stopping distances were shorter than for the comparable stops made with the anti-lock braking systems activated.

But unlike the stops made with the anti-lock system activated the tires slid off the powerstrip. The left front tire consistently slid off the strip to the right and the left rear tire slid off the powerstrip to the left. The strip clearly has the potential to serve as a skid inducer even when the powerstrip is dry and the speeds traveled are relatively slow. It is also clear that stopping distances are greatly extended when automobile tires are on top of the powerstrip.

The prototype of the powerstrip and the method to adhere the strip to the roadway surface did not withstand the stress of just a few quick stops. Both the rubber holder and the steel tubes moved about at even the lowest speeds. During the 30 mile per hour test stop two steel tubes were displaced from the rubber holder and the holder slid out of place.

IV. SUMMARY AND IMPLICATIONS OF THE FINDINGS

A. Responses to the presence of the power strip.

Pedestrian behavior was not affected by the presence of the powerstrip. However driver behavior did change. Half (72 of 144) of all drivers took action to avoid the powerstrip. Pedestrians did not avoid the powerstrip and forty-five percent of pedestrians who encountered the powerstrip stepped on it. Pedestrians also were observed in close proximity of the bus and with the large number of pedestrians who stepped on the powerstrip it appears that the only way to avoid having a
pedestrian exposed to electricity is to design the powerstrip system to insure that no electricity is present when pedestrians are present.

With half of all drivers taking action to avoid the powerstrip the potential does exist for increased risk of collisions on a roadway where the powerstrip is present. The collisions would occur when drivers leave the center of the lane to avoid the powerstrip and encounter parked vehicles when they move to the right, and oncoming vehicles when they move to the left.

With the exception of the change in drivers behavior, the public accepted the presence of the powerstrip and did not express concern for their safety or the safety of others during the short time the powerstrip was in the driving environment.

B. Impact of the power strip on vehicle performance.

The findings clearly indicate that the powerstrip adversely affects the stopping distance of an automobile. The powerstrip also has the potential to induce skidding. The lengthening of stopping distance and skid induction potential will both be magnified when the pavement and powerstrip are wet. The powerstrip's skid induction potential can be attributed to the profile of the strip and the low coefficient of friction of the rubber and steel composition of the powerstrip. The skid induction potential is a function of reduced friction and slope in horizontal profile of the powerstrip. It is possible that reducing the slope in horizontal profile of the powerstrip and increasing the coefficient of friction of the powerstrip could reduce the skid inducting potential of the powerstrip.

A lower profile and an increased coefficient of friction would also reduce the problems of braking on top of the power strip with two wheeled vehicles. Lowering the profile of the powerstrip also has the potential to reduce the tripping effect of the powerstrip on roller blades.

An adverse effect of increased friction is the added stress placed on the components of the powerstrip when a braking tire is on top of the powerstrip. The powerstrip was not able to withstand the stress placed on it when braking tires were on top of the powerstrip even with the low friction of the present design. Increasing the friction increases the stress placed on the powerstrip. It is a reasonable extension of the current study's findings with regard to braking's
effect on the strip to assume that a braking tire moving at an angle to the powerstrip will lose traction when the braking tire hits the powerstrip. The current study does not document the precise impact this loss of traction will have on vehicle performance, but it is a reasonable assumption that the impact will adversely affect vehicle performance. Based on the damage done to the powerstrip when braking tires were running parallel to the strip it can reasonably be assumed the powerstrip would be damaged when a braking tire hits the power strip at an angle.

The proto-type of the powerstrip proved to be inadequate to withstand the stress placed on both the components of the powerstrip and the points of adhesion between the pavement surface and the powerstrip by braking tires. Further testing of the current proto-type would not be of value since it is clear that improvements need to be made in the powerstrip design.

The powerstrip did not adversely affect lane changing for two types of bike tires and automobile tires at various speeds and angles of crossing. The profile of the powerstrip did create problems for roller bladers who do not step over or jump the strip. Lowering the profile of the powerstrip may prove to reduce the negative impact on roller bladers. The slipperiness of the powerstrip in its current design does present two wheeled high users with a major challenge if these users need to stop when their tires are on the powerstrip. The test riders were not willing to test stopping with the tires of their bikes on the powerstrip because they believed that falling was a near certainty.

V. RECOMMENDATIONS

In response to the findings of this study the following recommendations are offered:

- an appropriate warning sign should be designed and tested to advise drivers to stay in their lane rather than avoid the powerstrip.
- additional warning signs for pedestrians and roller bladers should be designed and tested to discourage stepping on or rolling over the powerstrip.
- the lack of concern by pedestrians during these test underscores the need to develop a power delivery system that reliably minimizes the time that live powerstrips are accessible to humans.
- the powerstrip should be redesigned to increase its coefficient of friction and lower its profile.
any design modifications to the powerstrip should consider a need to be snow plow proof.

additional tests with the a redesigned powerstrip should be undertaken to determine the
durability of the strip with regard to a wide variety of situations where a braking tire passes
over the powerstrip.

a better method to adhere the component parts to each other and the roadway surface must
be developed and tested before the powerstrip is placed on a roadway.

the redesigned powerstrip should be tested for its impact on lane changing by all types of
highway users including vehicles that have not been properly maintained (e.g. low tire
pressure).

the redesigned powerstrip should be tested for its impact on stopping distance, lateral
control, accelerating, and skid inducing characteristics under a wide variety of road and
weather conditions.
Bus Stop
Cross Walk

Length of Strip: 110 feet
Distance the strip is: 9 feet

Test Strip

Width of Road: 27 feet
Length of Viewed Road: 130 feet
Curb Height: 6 inches

Observation Point

Figure 6-1
Diagram of Test Site
I. INTRODUCTION

This report is part of a larger study to determine the feasibility of the E-TRAN electric vehicle system. Included in the Evaluation Plan for this larger study is Safety Test 7: Effect on Road Drainage.

The E-TRAN Electric Vehicle System is a trolley type system which requires contact between a pantograph and a power source. The power source is located on the surface of the roadway and in the center of the traveled lane. Since a typical roadway is crowned at the centerline or on a laneline, the E-TRAN powerstrip could act as a dam. The purpose of this report is to determine theoretically if the E-TRAN powerstrip base can be modified to allow for drainage underneath the conduit.

II. THEORY

The hydraulic analysis will follow standard procedures used on Minnesota roadways to determine the flow rate in cubic feet per second (Q). Q will be calculated using the Rational Method. The Rational Method\(^1\), which can be traced to the mid-nineteenth century, is probably the most widely used method of determining flow rates because of its simplicity. While valid criticisms have been raised about the adequacy of this method, its use on small watersheds—such as those related to this study, is universally accepted. The Rational Method is as follows:

\[
Q = CIA
\]

where

- \(Q\) = Flow Rate in Cubic Feet per Second
- \(C\) = Runoff Coefficient (a dimensionless factor \(0<C<1\))
- \(I\) = Rainfall Intensity in Inches per Hour
- \(A\) = Runoff Area in Acres

---

The Runoff Coefficient, \( C \), is a variable chosen by the hydrologist and depends on the imperviousness of the surface, the slope of the surface and the ponding characteristics of the surface. Impervious surfaces, such as pavements, will produce nearly 100% runoff—meaning the Runoff Coefficient will be high. Traditional practice has \( C = 0.9 \) for pavement surfaces. With respect to the E-TRAN system, it is assumed that all surfaces will be paved within the runoff area.

The Rainfall Intensity, \( I \), is the average rainfall rate in inches per hour for a particular drainage area. The intensity is a function of the time of concentration of the storm and the design return period of the storm. The time of concentration of the storm is the time it takes for a drop of water to travel from the most remote point in the drainage area to the point of interest, which, in the case of E-TRAN, would be the power strip. The design return period of the storm is established by design standards or chosen by the hydrologist as a design parameter. Typical design return periods are 1, 5, 10, 25, 50 and 100 years. A design storm for a 50 year design return period would theoretically return once every 50 years. The Rainfall Intensity, \( I \), for a certain location can be found by reading a value from a chart. The Minnesota chart is shown in figure 1, taken from the 1968 Minnesota Department of Transportation Drainage Manual.

The Runoff Area, \( A \), in acres, is simply the area which contributes runoff to the point of interest. For this study, the assumption is that the area contributing runoff to a certain point along the E-TRAN powerstrip will all be paved and will be the area with a width equal to the distance from the powerstrip to the road crown or the superelevation breakpoint and a length which is determined by the longitudinal grade of the roadway and the distance between outlets.

When these variables have been determined, the flow accumulating at any point along the powerstrip can be calculated. With this \( Q \), the size and spacing of the outlets or openings in the E-TRAN base can be determined.
FIGURE 1

RAINFALL INTENSITY - DURATION - FREQUENCY CURVES
For use with rational formula
III. ANALYSIS PARAMETERS

In order to study the drainage issue properly, two scenarios are going to be analyzed. The first scenario will be a standard 2-lane, 2-way bituminous roadway on tangent with a cross slope of 1.5ft/100ft (.015%). The assumption will be that the lanes are 12 feet wide and the powerstrip is attached to the roadway 6 feet from the centerline. (see figure 2) This, in affect, is a best case scenario. The second scenario will be a 4-lane undivided bituminous roadway on a horizontal curve. The horizontal curve will necessitate a superelevation in the cross slope similar to a "banked turn" on a race track. The cross slope will be 6ft/100ft, (.06%) which is the maximum allowable superelevation in the state of Minnesota. Again, the assumption is that the lanes are 12 feet wide, but the powerstrip is attached to the road 6 feet from the edge of the traveled lane on the low side of the superelevation. (see figure 3) This is a worst case scenario. (While there are roadway sections in the United States with greater than 4 lanes superelevated in one direction, some sort of longitudinal drainage is required to meet design criteria.) As can be readily ascertained from figures 1 and 2, vastly different widths of roadway are contributing runoff to accumulate at the powerstrip. This will cause significant differences in A, the runoff area.

The analysis parameters must also include the design return period of the storm. Typically, on Minnesota roadways, a 10 year design return period is used for drainage system design and a 100 year design return period is used for pond design. The E-TRAN system will be required to meet the requirements of an urban storm sewer system as far as lane encroachment and flowby. Therefore, a 10 year design return period will be used. To be conservative, a time of concentration of 10 minutes will be used for all analysis. The Rainfall Intensity, I can then be found from figure 3 to be 5.6 inches/hour.

The Area, A, will vary depending on which scenario we are analyzing, as we discussed earlier. The area will also vary depending on the longitudinal length of the roadway which is contributing runoff to the opening in the E-TRAN system. This variance will be directly related to the spacing in the openings in the rubber base of the powerstrip. For example, if the openings are spaced 100 feet apart and the width of contributing roadway is 6 feet, as in scenario 1, the area will be 100ft*6ft=600 square feet. 600 square feet/43560 square feet per acre = 0.0138 acres. In this example, Q would equal the following: 0.9*5.6*0.0138=0.0694 cubic feet per second. The conversion from acre*in!hour to cubic feet/second is included in the runoff coefficient. Table 1 calculates Q for scenarios 1 and 2 for a wide range of drainage opening spacings.

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2 Minnesota Department of Transportation, Road Design Manual, 1983
Two-Lane Urban Section

FIGURE 2

---

Four-Lane Urban Section

FIGURE 3
IV. ANALYSIS

When the flow rate has been determined, the velocity can be calculated using Manning's Equation for open channel flow. Using Manning's Equation, the velocity will vary with the size of the opening. Once the velocity is calculated, the flow rate \( Q \) can be found by multiplying the velocity, \( V \) by the area of the opening, \( A \). These values for \( Q \) can then be compared to the values in Table 1. Manning's Equation is as follows:

\[
V = \frac{1.49 R^{2/3} S^{1/2}}{n}
\]

where \( V \) = Velocity in Feet/Second  
\( n \) = Manning's Roughness Coefficient  
\( R \) = Hydraulic Radius  
\( S \) = Slope in Feet/Foot

The Hydraulic Radius, \( R \), is the area of flow, \( A \), divided by the Wetted Perimeter, \( P \). Manning's Roughness Coefficient, \( n \), is a dimensionless constant which varies with the type of surface. For the purposes of this report, the surface is bituminous and \( n=0.012 \). The slope, \( S \), is the slope of the pavement the water is flowing across. This value will be either 0.015 or 0.06, depending on which scenario is being studied. Table 2 calculates \( V \) and \( Q \) for a range of opening sizes for both scenarios.

V. CONCLUSIONS AND RECOMMENDATIONS

Comparing the flow rates in the tables for both scenarios, it is readily apparent that with proper sizing and spacing of openings, the flow rates through the E-TRAN base can be greater than the flow rates produced for a 10 year storm. These calculations, however, only prove that it is possible to drain a 10 year storm from the pavement by providing openings in the E-TRAN rubber base. There are several other concerns which must be addressed regarding this issue. First of all, given the height of the opening (1" or .0833'), sediment buildup, debris or ice would block a significant portion of the openings at all times. The hydraulic design of the E-TRAN base would require a safety factor on the order of 4 or more to adequately provide drainage of the roadway. Also, a heated power strip would help to keep ice from building up on the conduit. Second, the operational characteristics /cost effectiveness of the E-TRAN system have not been studied with regard to the openings in the rubber base. Third, the effects of “funneling” a large amount of water through one location in the rubber base could have adverse safety effects on the low side of the power strip.
My recommendations for the E-TRAN system with respect to the issue of drainage are as follows:
The rubber base should be redesigned with short openings spaced at close intervals. The opening length and the opening interval should be evaluated on a job by job basis from both a civil (drainage) and mechanical (operations) engineer.

The system should include a heated cable to melt ice and snow.

The system should undergo operational testing to test both the drainage characteristics and operational characteristics of the redesigned powerstrip system.

The E-TRAN system should be designed to fit the drainage parameters of the individual project.

The powerstrip should be kept as free of debris as possible to enhance the drainage characteristics of the roadway.

V. DISCLAIMER

This report simulates conditions which could be encountered on a public roadway using universally accepted drainage design practices and procedures. Because this analysis is purely theoretical, the computations contained herein shall not be used as the basis for final design of the E-TRAN system.
### SAFETY TEST 7

#### TABLE 1

**MAXIMUM FLOW RATES DURING A 10 YEAR STORM BASED ON THE RATIONAL FORMULA**

<table>
<thead>
<tr>
<th>OPENING SPACING (FEET)</th>
<th>WIDTH (FEET)</th>
<th>AREA, A (ACRES)</th>
<th>RUNOFF COEFFICIENT, C</th>
<th>RAINFALL INTENSITY, I (INCHES/HR)</th>
<th>FLOW RATE, Q (CUBIC FT/SEC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>6</td>
<td>42</td>
<td>0.001</td>
<td>0.9</td>
<td>5.6</td>
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<td>20</td>
<td>6</td>
<td>42</td>
<td>0.003</td>
<td>0.9</td>
<td>5.6</td>
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<tr>
<td>30</td>
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<td>0.004</td>
<td>0.9</td>
<td>5.6</td>
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<tr>
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<td>0.006</td>
<td>0.9</td>
<td>5.6</td>
</tr>
<tr>
<td>50</td>
<td>6</td>
<td>42</td>
<td>0.007</td>
<td>0.9</td>
<td>5.6</td>
</tr>
<tr>
<td>60</td>
<td>6</td>
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<td>0.008</td>
<td>0.9</td>
<td>5.6</td>
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<tr>
<td>70</td>
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<td>0.9</td>
<td>5.6</td>
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<td>0.011</td>
<td>0.9</td>
<td>5.6</td>
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<td>0.012</td>
<td>0.9</td>
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</tr>
<tr>
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<td>0.014</td>
<td>0.9</td>
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<td>0.021</td>
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<td>0.028</td>
<td>0.9</td>
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</tr>
<tr>
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<td>6</td>
<td>42</td>
<td>0.041</td>
<td>0.9</td>
<td>5.6</td>
</tr>
</tbody>
</table>
### SAFETY TEST 7

**TABLE 2**

**MAXIMUM FLOW RATES THROUGH OPENINGS IN E-TRAN BASE**

**BASED ON MANNING'S EQUATION FOR OPEN CHANNEL FLOW**

<table>
<thead>
<tr>
<th>OPENING HEIGHT (FEET)</th>
<th>WIDTH (FEET)</th>
<th>AREA, A (SQ. FEET)</th>
<th>B</th>
<th>WETTED PERIMETER, P (FEET)</th>
<th>HYDRAULIC RADIUS, R (FEET)</th>
<th>SLOPE, S</th>
<th>VELOCITY, V (FEET/SEC)</th>
<th>FLOW RATE, Q (CUB. FT/SEC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.083</td>
<td>0.6</td>
<td>0.042</td>
<td>0.12</td>
<td>0.87</td>
<td>0.0625</td>
<td>0.015</td>
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<td>2.3923</td>
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<td>0.0714</td>
<td>0.015</td>
<td>0.06</td>
<td>2.6151</td>
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<td>0.083</td>
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<td>0.125</td>
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<td>2.7781</td>
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<td>0.12</td>
<td>3.17</td>
<td>0.0899</td>
<td>0.015</td>
<td>0.06</td>
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<td>0.0819</td>
<td>0.015</td>
<td>0.06</td>
<td>2.8654</td>
</tr>
</tbody>
</table>
Technology Test 1: Dynamometer Tests

P.I. Mike Lehn
Technical Director: Nick Musachio
Technical Assistant: John Flaschenriem

April 13, 1995

Research Issue
These tests had two purposes: 1) To determine the efficiency of the E-TRAN Vehicles and 2) To determine the effects contaminants such as dirt, sand, snow, and salty slush on the performance of the system.

System Efficiency
The tests run with the E-TRAN vehicle were done on a dynamometer using the E-TRAN Isuzu Trooper conversion. (See photo.) This vehicle has both an electric E-TRAN powered electric motor and a gasoline engine on the same drive train. The efficiency of the vehicle was determined by converting the number of kilowatt hours used per mile to the number of British Thermal Units (BTUs) used per mile. Electrical use was measured at the three phase 230 volt outlet which powered the vehicle. Approximately 10,000 BTUs are needed for a modern electric power plant to deliver one kilowatt hour of electricity taking into account line and transmission losses. By converting miles per gallon to BTUs per gallon a comparison and conversion can be made. One gallon of gasoline contains 125,000 BTUs. Thus a vehicle getting 25 miles per gallon could be said to use 5,000 BTUs/mile. (125,000 BTU's/gallon divided by 25 miles/gallon). Likewise, a car using .5 kilowatt hours per mile would use 10,000 BTUs/kilowatt *.5 kilowatts/mile which equals 5,000 BTU's per mile, or the equivalent of 25 miles per gallon.

Contaminants Effect on Performance
The dynamometer was also used to determine the effects of contaminants on the performance of the E-TRAN system. This was done by putting the vehicle on a dynamometer then placing an E-TRAN strip beneath the vehicle, then powering the E-TRAN vehicle from the strip through the contacting system. Once the strip was placed beneath the vehicle, dirt, sand, snow, and salty slush were placed on the strip. Since the dynamometer holds the vehicle steady, the strips themselves were moved during the running of the vehicle. Additionally, the vehicle's batteries were disconnected so that only power from the wall was used. The vehicle was then observed for performance and electrical use.
Results

Efficiency: The efficiency of the E-TRAN vehicle in real terms, assuming electricity being generated by a coal burning power plant was about twice that of the gasoline powered Isuzu Trooper. At thirty miles per hour the test vehicle attained 32 miles per gallon on the freewheeling dynamometer when powered by gasoline. Gasoline has approximately 125,000 BTU's per gallon. Using this assumption, BTU's per mile can be found using the formula BTU's/gallon divided by miles/gallon = BTU's/mile. At 125,000 BTUs/gallons, 32 miles per gallon equals 3906 BTUs per mile. Electrical consumption at 30 miles per hour was 6,289 watt hours/30 miles, or 209.6 watt hours per mile, which equals 2,096 BTUs per mile (one watt hour equals 10 BTUs -- 1 kilowatt equals 1,000 watts equals 10,000 BTU's). Electrical power use was determined by taking the Average Amperage draw from the 230 volt 3 phase system times voltage times 1.73. The formula used for power consumption of a three phase system is Amp 1 + Amp2 + Amp3/3*voltage*1.73. Comparing the BTU figure obtained from gas and electricity, 3906 BTUs/mile of gas to 2,096 BTUs/mile of electricity the electric drive used 53.6% as much energy as the gasoline drive. This is a 46% reduction in energy consumption in real terms. In other words, the electric drive train was nearly twice as energy efficient as the gasoline drive train.

Contaminants: The results of the dynamometer testing indicated that contaminants on the power strip had little effect on the efficacy of power transmission between the conductors and the power collection system. Adding contamination to the conductive strips did not affect change the voltage by more than one percent in any case. Certain contaminantants actually seemed to increase efficiency. See following chart. Additionally, movement and bouncing had no effect on the electric transmission efficiency.

Voltages to vehicle under varying conditions through E-TRAN system.

<table>
<thead>
<tr>
<th>Speed (mph)</th>
<th>Clean</th>
<th>Dirt</th>
<th>Sand</th>
<th>Salt/Slush</th>
<th>Volts</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>327</td>
<td>327</td>
<td>329</td>
<td>329</td>
<td>Volts</td>
</tr>
<tr>
<td>10</td>
<td>326</td>
<td>326</td>
<td>328</td>
<td>327</td>
<td>Volts</td>
</tr>
<tr>
<td>20</td>
<td>324</td>
<td>324</td>
<td>326</td>
<td>326</td>
<td>Volts</td>
</tr>
<tr>
<td>30</td>
<td>322</td>
<td>322</td>
<td>324</td>
<td>324</td>
<td>Volts</td>
</tr>
<tr>
<td>40</td>
<td>319</td>
<td>319</td>
<td>321</td>
<td>320</td>
<td>Volts</td>
</tr>
</tbody>
</table>
Movement with sand caused some intermittent sparking, but caused no performance decrease. Salty slush contamination actually seemed to increase voltage to the vehicle. The tests were carried out using no batteries in the vehicle so that significant power interruptions or voltage variations would show up immediately by stalling the vehicle which has a power interruption shut down safety feature.

**Conclusions**

**Efficiency:** The electric drive on the vehicle operated at about twice the efficiency as the gasoline drive in real terms. This is consistent with previous testing conducted by the U.S. Department of Energy in the comparison of gasoline and electric modes.

**Contaminants and Performance:** Unless the amount of debris on the strips actually lifts the pantograph assembly from the conductors, electricity can be transferred through the system with little change in efficiency in dirty environments. The pantograph collection assembly cleans and clears the strips of debris and contaminants as it slides on the conductive strips.

**Recommendations**

The following recommendations would aid in the development of an E-TRAN transit system.

The pantograph assembly plays a significant role in power collection. 1) Great care in design must be taken to assure that the contacting mechanism produces a solid contact with the power strips. Future generations of system design err on the side of excess contact area. By the same token, a clean contact is more important than contact area. Thus, 2) Future designs must also assure that the track clearing function is optimized. 3) Carefully consider collector brush material. The existing copper graphite material works well. The collector brush on the pantograph cleans, polishes, and coats the track with a patina that prevents corrosion, dissipates heat, and reduces friction. 4) Finally, further real world and higher speed testing is the next logical testing step.

**Steps Needed For Implementation**

The steps needed for implementation would be as follows.

Set up larger real world testing site that allows for higher speed and power.

Carefully research the materials selected for electric collector brush design.

In the redesign accent track clearing properties as well as contact area. Design should also include provisions for varying the tension of the collector bars.
### Technology Test 1: Dynamometer Performance Testing

**Data Sheet**

P.I. Mike Lehn  
St. Cloud Technical College

**Date of Testing 2-22-95**

<table>
<thead>
<tr>
<th>MPH</th>
<th>MPH</th>
<th>MPH</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>30</td>
<td>40</td>
</tr>
</tbody>
</table>

**Gas Horsepower**

<table>
<thead>
<tr>
<th>Gas Miles per Gallon</th>
<th>32 mpg</th>
</tr>
</thead>
</table>

**Stationary clean strip**

**Vector Drive**

<table>
<thead>
<tr>
<th>Horsepower at wheels</th>
<th>38</th>
<th>20</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>RPM</td>
<td>1730</td>
<td>3523</td>
<td>4537</td>
</tr>
<tr>
<td>Volts</td>
<td>13.9</td>
<td>22.8</td>
<td>53.9</td>
</tr>
<tr>
<td>Watts</td>
<td>308</td>
<td>226</td>
<td>336</td>
</tr>
</tbody>
</table>

**Data taken from Vector drive**

**Electric From Wall**

<table>
<thead>
<tr>
<th>Volts in vehicle</th>
<th>327</th>
<th>324</th>
<th>320</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amp 1</td>
<td>7</td>
<td>14</td>
<td>24</td>
</tr>
<tr>
<td>Amp 2</td>
<td>4</td>
<td>12</td>
<td>23</td>
</tr>
<tr>
<td>Amp 3</td>
<td>10</td>
<td>19</td>
<td>31</td>
</tr>
<tr>
<td>Watts</td>
<td>2,935.09</td>
<td>6,289.47</td>
<td>10,901.75</td>
</tr>
<tr>
<td>BTU's per mile</td>
<td>1,957</td>
<td>2,096</td>
<td>2,725</td>
</tr>
<tr>
<td>Miles per gallon equivalent*</td>
<td>64</td>
<td>60</td>
<td>46</td>
</tr>
</tbody>
</table>

* Based on 10,000 BTU's per Kilowatt, and 125,000 Btu's per gallon of gas
Technology Test 1: Dynamometer Performance Testing
Data Sheet

2/23/95: 2:30 PM
Volts at Rectifiers 337
Stationary/clean strip
Batteries in Vehicle

<table>
<thead>
<tr>
<th>MPH</th>
<th>Volts in Vehicle</th>
<th>Amps</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 MPH</td>
<td>327</td>
<td>1</td>
</tr>
<tr>
<td>10 MPH</td>
<td>326</td>
<td>13.5</td>
</tr>
<tr>
<td>20 MPH</td>
<td>324</td>
<td>16.2</td>
</tr>
<tr>
<td>30 MPH</td>
<td>322</td>
<td>25.8</td>
</tr>
<tr>
<td>40 MPH</td>
<td>319</td>
<td>88</td>
</tr>
</tbody>
</table>

Motion and bouncing showed no change
Volts at rectifiers 337
Dirt no batteries used

<table>
<thead>
<tr>
<th>MPH</th>
<th>Volts in Vehicle</th>
<th>Amps</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>331</td>
<td>1.3</td>
</tr>
<tr>
<td>10</td>
<td>327</td>
<td>13.8</td>
</tr>
<tr>
<td>20</td>
<td>325</td>
<td>17.2</td>
</tr>
<tr>
<td>30</td>
<td>324</td>
<td>26.1</td>
</tr>
<tr>
<td>40</td>
<td>321</td>
<td>46</td>
</tr>
</tbody>
</table>

Bouncing and movement showed no changes
Dirt covered 24" of track approximately .5 inches high. 1 quart of dirt dumped directly onto track
Sand
Technology Test 1: Dynamometer Performance Testing
Data Sheet

<table>
<thead>
<tr>
<th>MPH</th>
<th>Volts in Vehicle</th>
<th>Amps</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
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<td>13</td>
</tr>
<tr>
<td>10</td>
<td>328</td>
<td>14.7</td>
</tr>
<tr>
<td>20</td>
<td>326</td>
<td>14.3</td>
</tr>
<tr>
<td>30</td>
<td>324</td>
<td>24.4</td>
</tr>
<tr>
<td>40</td>
<td>321</td>
<td>49.8</td>
</tr>
</tbody>
</table>

Movement back and forth and sideways caused no performance or voltage differences but did cause occasional sparking.

Snow, salt, sand and water
One gallon of slush, salt, sand from actual roadway, dumped onto track

<table>
<thead>
<tr>
<th>MPH</th>
<th>Volts in Vehicle</th>
<th>Amps</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
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<td>13</td>
</tr>
<tr>
<td>10</td>
<td>327</td>
<td>13.7</td>
</tr>
<tr>
<td>20</td>
<td>326</td>
<td>12.3</td>
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<td>324</td>
<td>19.3</td>
</tr>
<tr>
<td>40</td>
<td>320</td>
<td>44</td>
</tr>
</tbody>
</table>

Movement caused no difference. Their was less sparking than dry sand. Performance seemed better than dry.

Resistance check showed .02 ohms of resistance stationary and .01 ohms of resistance with movement.
Technology Test 1: Dynamometer Performance Testing
Data Sheet

Bus Dynomometer Testing
3-3-95, 12:30 PM
John Kline and Nick Musachio

<table>
<thead>
<tr>
<th>Horsepower</th>
<th>KW's</th>
<th>Miles per Gallon Equivalent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bus 15 mph</td>
<td></td>
<td></td>
</tr>
<tr>
<td>gas 2nd gear high</td>
<td>35</td>
<td></td>
</tr>
<tr>
<td>gas 2nd gear low range</td>
<td>32</td>
<td></td>
</tr>
<tr>
<td>Electric 14.5 mph</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3rd gear 105 v @350A</td>
<td>4</td>
<td>36.75</td>
</tr>
<tr>
<td>Electric 10 mph in 3rd</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>4th gear Elect</td>
<td>3</td>
<td></td>
</tr>
</tbody>
</table>

Max Dynamometer Speed with Electric Motor = 15mph

Contaminants on strip testing
Contaminants were put on approximately 2 feet of track on three contacts
Approximately 1 quart of material was used except for snow in which 1 gallon was used
Tests done @ 114 volts at 100 amps

<table>
<thead>
<tr>
<th>Source voltage</th>
<th>To Motor</th>
<th>Voltage Drop</th>
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</thead>
<tbody>
<tr>
<td>Clean Strip</td>
<td>114</td>
<td>109</td>
</tr>
<tr>
<td>with movement</td>
<td>114</td>
<td>109</td>
</tr>
<tr>
<td>Sand Dry</td>
<td>114</td>
<td>109</td>
</tr>
<tr>
<td>with movement</td>
<td>114</td>
<td>109</td>
</tr>
<tr>
<td>dirt- muddy and wet</td>
<td>114</td>
<td>109</td>
</tr>
<tr>
<td>with movement</td>
<td>114</td>
<td>109</td>
</tr>
<tr>
<td>snow</td>
<td>114</td>
<td>109</td>
</tr>
<tr>
<td>with movement</td>
<td>114</td>
<td>109</td>
</tr>
<tr>
<td>slush w sand dirt, and salt</td>
<td>114</td>
<td>109</td>
</tr>
<tr>
<td>w movement</td>
<td>same</td>
<td>109</td>
</tr>
</tbody>
</table>

Voltage drop at 200 amps was 10 volts- or twice what it was at 100 amps.
## Technology Test 1: Dynamometer Performance Testing

Data Sheet

### SUMMARY

<table>
<thead>
<tr>
<th>Source voltage</th>
<th>To Motor</th>
<th>Voltage Drop</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clean Strip</td>
<td>114</td>
<td>109</td>
</tr>
<tr>
<td>Sand Dry</td>
<td>114</td>
<td>109</td>
</tr>
<tr>
<td>Dirt</td>
<td>114</td>
<td>109</td>
</tr>
<tr>
<td>snow</td>
<td>114</td>
<td>109</td>
</tr>
<tr>
<td>Salt/slush</td>
<td>114</td>
<td>109</td>
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</tbody>
</table>

### Measurements

<table>
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<th>Clean Strip</th>
<th>Dirt</th>
<th>Sand</th>
<th>Salt/slush</th>
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<tbody>
<tr>
<td>0 mph</td>
<td>327</td>
<td>327</td>
<td>329</td>
</tr>
<tr>
<td>10 mph</td>
<td>326</td>
<td>326</td>
<td>328</td>
</tr>
<tr>
<td>20 mph</td>
<td>324</td>
<td>324</td>
<td>326</td>
</tr>
<tr>
<td>30 mph</td>
<td>322</td>
<td>322</td>
<td>324</td>
</tr>
<tr>
<td>40 mph</td>
<td>319</td>
<td>319</td>
<td>321</td>
</tr>
</tbody>
</table>
Technology Test 2: Adverse Performance Conditions

P.I. Mike Lehn
Technical Director: Nick Musachio,
Technical Support: John Flaschenriem
Observer: Roger Young, SCTC Instrumentation Instructor.

April 23, 1995

Research Issue
Technology Test 2 complements Technology Test 1, Dynamometer Testing. Real world applications of E-TRAN will have dirt, sand, dust, and snow as well as other contaminants on the system. The system must function in spite of these impediments. Technology Test 2 tests the effects of contaminants on the track as relative to the performance of the test vehicle. Various contaminants are placed on a twenty foot section of the track. Then the vehicle is driven around the track to determine what effect a particular contaminant has on performance. Electrical measurements are taken to determine the effectiveness of electrical transference when contaminants are present. Note: Bill Thiesse of Erickson and Ellison did not participate in this test.

Results
The results of the testing concurred with the dynamometer tests. Dirt, sand, snow, and salty slush had no perceived effect on performance. Voltage in the vehicle remained the same in spite of contaminants. There were no power interruptions. The front collector brush acts as a track cleaner and cleans the debris from the track allowing the system to function normally. After one revolution the top of the power strip appears clean of debris placed directly on it. The debris is knocked to either side. See photos.

Conclusions
The conclusions from the testing are:
1) Unless unusually large amounts of contaminants are present - to the point in which the pantograph is physically lifted from the track - the front pantograph will act as a track cleaner/clearer and knock or clear contaminants to either side of the track allowing uninterrupted operation.
2) Dirt, sand, slush, and snow, does not impede vehicle operation. These results are consistent with dynamometer tests as well as third rail operations which encounter similar situations with contaminants.

**Recommendations**

Since the first collector brush acts as a cleaner or clearer of the track it would be wise to be cognizant of that function and cater to it when designing future systems. It would be recommended to explore the following features:

1) Addition of a pre-collector clearing mechanism to act as a cow-catcher device for the pantograph collector mechanism. This device may be of a non conductive nature such as nylon.

2) Addition of a variable tensioning device to vary tension according to conditions. For example, more pressure may be needed in snow or slush conditions, higher speeds, or higher power needs.

3) Planning of provisions for monitoring and the preventive cleaning of snow and road debris.

4) Real world testing on a track or public street.

**Steps Needed For Implementation**

The steps needed for implementation would be:

1) Redesign pantograph with variable tensioning device so that tension between strip and collector brush can be varied.

2) Redesign collectors to explore various track clearing properties of pantograph.

3) Place strip on a roadway for an extended period of testing to determine the effects of road debris.

**Recommendations**

Although the basic operation of the system intrinsically cleans debris from the power strips as the vehicle moves, it would be wise to keep the following recommendations in mind to optimize the intrinsic properties of the technology that allow the system to operate in dirty and contaminated conditions:

1. Study pantograph design to determine optimum downward pressure of collectors on pantograph.
2. In design, be mindful of the track clearing properties of the pantograph. Design the system so that the leading edge of the pantograph collector will act as a clearer and cleaner.

3. Rearward biasing to allow for the pantographs that bounces over debris works well and should be continued and refined.

4. Study properties of system at higher speeds, higher voltages, and higher amperages.

Steps for Implementation of Recommendations
The following steps are recommended:
1) Build a larger longer track to test higher powered higher speed applications.
2) Obtain a higher powered vehicle and motor to test hypotheses.
3) Redesign pantograph to allow for variable downward pressures. Study the electrical properties of the collectors at these differing pressures under various conditions.
Technology Test 2 Data Sheet
Adverse Performance Conditions
PI: Mike Lehn
Testers: Nick Musachie, John Flaschenriem

Date: 3/16/95 2:00 PM
Weather: 50F, sunny

Procedure: Disconnect batteries. Place adverse materials on strip, run vehicle and observe influence of materials.
Measure voltage changes to vehicle. Observe performance variations if any.

One at a time materials are placed on 15 foot sectors of track and vehicle runs over adverse material repeatedly.

<table>
<thead>
<tr>
<th>Adverse condition</th>
<th>Performance Decrease y/n</th>
<th>Track Self Cleaned y/n</th>
<th>Volts/ Track</th>
<th>Volts/in vehicle*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clean</td>
<td>na</td>
<td>yes</td>
<td>337</td>
<td>329</td>
</tr>
<tr>
<td>Sand</td>
<td>no</td>
<td>yes</td>
<td>337</td>
<td>329</td>
</tr>
<tr>
<td>Dirt</td>
<td>no</td>
<td>yes</td>
<td>337</td>
<td>329</td>
</tr>
<tr>
<td>Leaves</td>
<td>no</td>
<td>yes</td>
<td>337</td>
<td>329</td>
</tr>
<tr>
<td>Salt Slush heavy</td>
<td>yes (1)</td>
<td>yes</td>
<td>337</td>
<td>329</td>
</tr>
<tr>
<td>Salt/slush light</td>
<td>no (2)</td>
<td>yes</td>
<td>337</td>
<td>329</td>
</tr>
<tr>
<td>Water</td>
<td>no</td>
<td>yes</td>
<td>337</td>
<td>329</td>
</tr>
</tbody>
</table>

Results: Vehicle pantograph knocked materials off of strip and continued to operate. No voltage drop was noticed. No performance change was noticed, except in heavy slush. These results are consistent with the dynanometer tests.

(1) In the condition of heavy slush the pantograph initially ran over slush and then after several passes wore the material down to a level that was even with the height of the conductive strip. With no batteries, this condition lead to a power interruption. With batteries this would not lead to a power interruption.
(2) In light slush the pantograph self cleaned immediately.

* Voltage varied between 330 and 290 due to track inconsistencies. 329 volts was the dominant voltage as the vehicle moved around the track. No change in voltage to the vehicle was perceived.

Adverse Condition: cold weather.
Will system work in cold weather? This question was answered in Safety Test 2.
During endurance runs the Trooper ran consistently through -20F temperatures with no problems.
This result is consistent with electric vehicle operation and electric theory in general.
Heat is usually a greater enemy than cold with electricity.
Technology Test 2 Data Sheet
Adverse Performance Conditions
PI: Mike Lehn
Testors: Nick Musachio, John Flashenriem

Date: 3/16/95 2:00 PM
Weather 50, sunny

Procedure: Place adverse materials on strip run vehicle and observe influence
Various materials are placed on track and performance is observed.
Materials are placed on 15 foot sectors of track and vehicle run for one hour @approx 8mph.

<table>
<thead>
<tr>
<th>Adverse material</th>
<th>Performance Decrease y/n</th>
<th>Track Self Cleaned y/n</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td>Dirt</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td>Leaves</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td>Slush</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td>Water</td>
<td>no</td>
<td>yes</td>
</tr>
</tbody>
</table>

Results: Vehicle pantograph knocked materials off of strip and continued to operate.
In the condition of slush the pantograph initially ran over slush and then after several passes wore the material down to a level that was even with the height of the conductive strip.
These results are consistent with the dynamometer tests.
I. INTRODUCTION

This report is part of a larger study to determine the feasibility of the E-TRAN electric vehicle system. Included in the Evaluation Plan for this larger study are Snow and Ice Tests 1 - 5. The E-TRAN system is a trolley type transportation system which requires electrical contact between the vehicle's power pick-ups (pantographs) and the power source. The power source is located beneath the vehicle on the roadway surface in the form of a cable with a rubber base. An obvious question arises pertaining to the implementation of the E-TRAN system in climates which are susceptible to snow and/or ice accumulation. The purpose of this report is to summarize the results of the snow and ice testing procedures. The scope of the testing procedures included the determination of the degree of cleanliness required for effective system operation and, the testing of several different procedures for removal of snow and ice from a roadway. The scope of the testing did not include repetitive snow removal procedures similar to what may occur in a real world application of the technology. The report will be organized as follows:

I. Introduction
II. Report Body
   A. Research Problem
   B. Test Descriptions
   C. Analysis of Test Results
   D. Recommendations/Preliminary Cost Analysis
III. Appendix
II. REPORT BODY

A. Research Problem

The component that makes the E-TRAN system truly unique in the transportation field is also the component which causes problems in the snow and ice removal area. The power strip, which lays on the roadway surface, parallel to the traveled lane, is a cable fabricated of conductive metal which is housed in a rubber base. The rubber base is attached to the roadway surface at certain intervals, causing the system to be somewhat rigid in nature. The powerstrip is attached to the roadway in the center of the lane, or between the wheel tracks of the vehicular traffic. Due to the design of the E-TRAN pantograph system, the powerstrip must protrude above the roadway surface approximately 1-1/2 to 2 inches. Because of the raised profile of the system, conventional plowing techniques may cause damage to the powerstrip. The testing procedures were designed to assess the problems related to conventional plowing, and provide alternative methods of snow and ice removal.

B. Test Descriptions

• SNOW AND ICE TEST #1
The purpose of Snow and Ice Test # 1 was to determine how clear the powerstrip must be for effective system operation. The strip and the roadway were covered with 4" of snow and system operation was attempted. The snow was then removed to a depth of 2" and the system was tested again. The testing differed slightly from the test plan here, the plan called for snow removal in 1" increments, 2" of snow were removed because of a decision made by the technical director and the plow operator. Finally, the snow was removed to a depth of 1", and system operation was attempted. In the second stage of test # 1, the powerstrip (but not the roadway) was covered with 4" of snow. The snow was removed incrementally down to 1" with system operation attempted at specific intervals. The third and final phase of test # 1 involved coating the powerstrip in ice and attempting operation of the E-TRAN vehicle.

• SNOW AND ICE TEST # 2
Snow and Ice Test #2 was designed to determine if existing snow removal equipment could effectively remove snow and ice from the system. The test required that various depths of snow be placed on the system and four methods of removal be attempted. The four methods included: precision plowing both sides of the powerstrip using a standard plow; precision plowing of the powerstrip using a booted plow; removing snow with a rotary brush type system; and using a
combination of a rotary brush and a booted plow. The results of all four of these procedures were compared to the results of test # 1.

- **SNOW AND ICE TEST #3**
The purpose of Snow and Ice Test # 3 was to determine the affects on the system when a standard full-size, front mounted plow with a carbide blade was utilized to remove snow. This test was to be attempted once, and the results measured against the results from test # 1.

- **SNOW AND ICE TEST #4**
Snow and Ice Test # 4 was designed to determine if application of standard chemicals would be a viable option to remove snow and ice. A standard sodium chloride mixture was placed on the powerstrip/roadway, which was covered with 2" of snow. The results were to be compared to the results of test # 1.

- **SNOW AND ICE TEST #5**
This test was designed to test the best alternative method of snow removal (found in the preceding tests), on a public street. The test was not done because the preferred alternative was not chosen until after the powerstrip was already removed from the Husky Shuttle route. An impromptu test was performed with a standard full-size plow on the shuttle route when the road was accidentally plowed by a city maintenance worker. The results of this impromptu test match the results of Snow and Ice Test # 3, the full-size plow damages the powerstrip.

**C. Analysis of Test Results**
The Data Collection Sheets for the various snow and ice tests are included in the appendix of this report. Test # 1, which determined how clean the powerstrip must be for efficient system operation, was performed on March 9, 1995, at the St. Cloud Technical College. The test procedure was designed to cover two scenarios. The first scenario covered both the powerstrip and the roadway with snow. The second scenario had just the powerstrip covered with snow. This test was intended to determine how much snow and/or ice could be left on the powerstrip while still allowing the E-TRAN system to operate. Both tests began with 4" of snow covering the system. In both tests, the pantograph could not make sufficient contact with the powerstrip to close the circuit. 2" of snow was removed from the strip and the system was tested again. In the first test (roadway and powerstrip covered), the pantograph made partial contact with the powerstrip, but not enough for operation. In the second part of the test (powerstrip only covered), the pantograph made sufficient contact with the powerstrip for operation. This was due to the fact that there was no snow under the tires of the vehicle, causing the pantograph to ride lower and
push the snow off of the powerstrip. Snow was then removed to a depth of 1" for both cases. In both cases, the system was operable. The third part of test # 1 was to cover the powerstrip with a layer of ice and test the system operations. The system was inoperable under these conditions because the pantograph had a tendency to glide over the powerstrip.

Snow and Ice Tests 2A - 2D and 3 were completed on March 9, 1995 at the City of St. Cloud Maintenance garage. Each test was performed three times in accordance with the test descriptions. Test 2A (precision plow both sides of strip) was attempted with snow depths of both 5" and 12". In both instances, snow removal was sufficient on the roadway but the strip was not clean enough to meet the criteria determined in test # 1 for system operation. Test 2B (use of booted plow) was attempted with a snow depth of 1'. The boots were set to a height of 2-1/2" - 3" and then the roadway was plowed. The snow removal was considered partial on both the roadway and the powerstrip. A problem was documented regarding the use of a front loaded plow in this test. The weight of the plow on the front of the vehicle causes some bouncing as the plow moves down the road. This can produce areas of the strip where the snow is not cleared to a sufficient depth for system operation. An additional test was attempted at this time using a booted belly plow (mounted on a road grader, between the axles) to correct the bouncing problem. This worked much better because the snow removal was consistent in terms of depth. Test 2C (use of brush mechanism) was attempted at 6" and 12". The snow was light and dry (optimum conditions for the use of a brush) and the brush removed the snow in all three tests sufficiently for normal system operation. Test 2D (a combination of the brush and the booted plow) was attempted 3 times with a snow depth of 1'. In all three tests, snow removal was satisfactory to allow normal system operation. This method would be the preferred alternative in cases where the snow was very deep (>1') or the snow was wet and heavy. Test # 3 (remove snow using a regular plow) was attempted several times with the plow blade held 3" above the ground. The results of this test were mixed. On the first try, the strip was damaged when the blade struck the powerstrip. The other two tests resulted in no damage, but the strip was not clean enough for system operation. In all Tests 2A -2D and 3, maintenance personnel estimated that if both the belly plow and the brush were mounted on one truck, the time required to clear snow and ice from the roadway/powerstrip would not be significantly longer than the time required to clear a normal roadway with standard equipment.

Test # 4 (use of standard chemicals) was completed on March 14, 1995 on a section of powerstrip at the City of St. Cloud Maintenance Garage. 2" of snow covered the powerstrip and 3" of ice was placed on a 10' section. The chemicals removed the snow and ice from the strip sufficiently to
allow normal operation of the E-TRAN vehicle. However, this method of removal created a slush on the pavement adjacent to the powerstrip which could cause problems for both the electrical operation of the powerstrip and the traffic operations on the roadway.

D. Recommendations/Preliminary Cost Analysis

Based on the testing, the following recommendations can be made regarding snow and ice removal:

- A front-end loaded plow is NOT recommended for use on streets equipped with the E-TRAN system.
- For lighter, dry snows (<1') a rotary brush mechanism should be used to remove snow from the powerstrip.
- For heavy (>1') or wet snows, a belly plow with boots should be used. These plows are in use on streets and roadways today, but are far less prevalent than the standard front-end loaded plows. The plow should be followed by a brush to clean the remaining snow from the road/powerstrip.
- The powerstrip should be equipped with a low wattage (~14 watts/foot) heating cable. While this was not included in the test plan, it was successfully used during Snow and Ice test # 2A. This heating cable will serve two purposes; one, to keep snow and ice from forming in the powerstrip and two, to help mark the strip so the snow plow operators can locate it when plowing.

The recommended alternative, a booted, belly mounted plow followed by a rotary brush to clear a powerstrip equipped with a low voltage heating cable would obviously have some additional costs relative to conventional snow plowing procedures. These costs can divided into several categories, capitol cost, maintenance and operation cost and labor/training cost. The capitol costs associated with this method of snow and ice removal are the easiest to quantify. Assuming that the agency in charge of maintaining the roadways equipped with the E-TRAN system owns a belly plow, the capitol cost would include the purchase of the brush mechanism and the inclusion of the heating cable in the powerstrip. These costs are estimated as follows:

- A 6 foot wide, 32" diameter brush which could be mounted on a belly plow vehicle would cost $6,5001.

---

1 The Sweepster Company
• An 8 foot wide, tow behind road sweeper would cost $12,400.
• The heating cable would incur an additional cost of between $1 and $10/linear foot for materials and installation.

The additional costs of the system related to maintenance and operations are not as readily available. While the testing indicated that damage to either the plowing equipment or the powerstrip did not occur, a real world application of the system may prove otherwise. With continued snow removal activity, the probability that even a booted belly plow would damage the powerstrip are high. The rate of occurrence of this damage could only be estimated through repeated snow removal procedures on a public street. The maintenance and operations costs of the brush mechanism and the heating cable can be more easily estimated:

• A replacement brush for the 6 foot wide brush system would cost $300. This brush would last about 150 hours or 1 winter season.
• The operational cost of heating the powerstrip would cost about $.05/linear foot/month.

The labor/training costs, again, are hard to quantify given the test data. Additional testing on a public street for a significant time period (one winter season) would provide data which could be compared to labor hours/training hours for conventional snow removal techniques.

In conclusion, my opinion given the test data is that a roadway equipped with the E-TRAN powerstrip system can be kept free of snow and ice using the preferred alternative of a belly mounted plow with boots and a brush. This method of snow and ice removal will be more costly than the removal methods used on a typical street. Because of testing constraints due to budgets and schedules, the preferred alternative has not been tested extensively on a public street. When this occurs, better, more efficient snow and ice removal methods may be identified.
E-TRAN ROAD POWERED ELECTRIC VEHICLE
SNOW AND ICE TESTS

TEST #1
PURPOSE: DETERMINE HOW CLEAR THE POWER STRIP SYSTEM MUST BE FOR EFFECTIVE OPERATION.

SCHEDULE: SEE ATTACHED OVERALL SCHEDULE

SAFETY PROCEDURES: OPERATE SNOW REMOVAL EQUIPMENT ON POWER STRIP ONLY WHEN THE POWER IS OFF.
MAINTAIN A MINIMUM DISTANCE OF TEN FEET FROM THE POWER STRIP AT ALL TIMES WHEN THE STRIP IS POWERED.
OBSERVERS MUST REMAIN A MINIMUM OF THIRTY FEET FROM THE BRUSH WHEN THE BRUSH IS IN USE.

SNOW AND ICE TESTS

TEST WILL BE CONDUCTED BY PLACING VARIOUS AMOUNTS OF ICE AND SNOW ON THE POWER STRIP AND REMOVING IT INCREMENTALLY WHILE TESTING SYSTEM OPERATION.

NICK MUSACHIO - TECHNICAL DIRECTOR
JOHN DILLINGHAM - ENGINEERING REVIEW
JOHN FLASCHENRIEM - OBSERVATION
JOHN HARPER - OBSERVATION
CITY MAINTENANCE CREWS - OBSERVATION

SEE DATA COLLECTION SHEET AND QUESTIONNAIRE

TEST A:
TEST A.1 ATTEMPT TO OPERATE THE RPEV, STARTING IN THE SNOW.
TEST A.2 ATTEMPT TO OPERATE THE RPEV, STARTING ON CLEAR POWERSTRIP AND DRIVING ONTO SNOW.
TEST A.3 REMOVE SNOW IN 1” INCREMENTS AND TEST THE RPEV UNTIL EFFECTIVE SYSTEM OPERATION IS ACHIEVED.

TEST B:
TEST B.1 ATTEMPT TO OPERATE THE RPEV, STARTING IN THE SNOW.
TEST B.2 ATTEMPT TO OPERATE THE RPEV, STARTING ON CLEAR POWERSTRIP AND DRIVING ONTO SNOW.
TEST B.3 REMOVE SNOW IN 1” INCREMENTS AND TEST THE RPEV UNTIL EFFECTIVE SYSTEM OPERATION IS ACHIEVED.

TEST C:
TEST C.1 ATTEMPT TO OPERATE THE RPEV, STARTING IN THE ICE.
TEST C.2 ATTEMPT TO OPERATE THE RPEV, STARTING ON CLEAR POWERSTRIP AND DRIVING ONTO ICE.

COVER THE POWERSTRIP AND THE ROADWAY SURFACE WITH 4" OF SNOW.
COVER THE POWERSTRIP (BUT NOT THE ROADWAY) SURFACE WITH 4" OF SNOW.
COAT THE POWER STRIP WITH WATER, LET FREEZE.

PERSONPOWER - 4 PEOPLE FOR 4 HOURS
EQUIPMENT - POWERSTRIP, ISUZU, BRUSH

SEE DATA COLLECTION SHEET AND QUESTIONNAIRE

PERSONPOWER - 4 PEOPLE FOR 4 HOURS
EQUIPMENT - POWERSTRIP, ISUZU, BRUSH

SEE DATA COLLECTION SHEET AND QUESTIONNAIRE

PERSONPOWER - 4 PEOPLE FOR 4 HOURS
EQUIPMENT - POWERSTRIP, ISUZU, BRUSH
E-TRAN ROAD POWERED ELECTRIC VEHICLE
SNOW AND ICE TESTS

PURPOSE: DETERMINE IF SNOW AND ICE CAN BE REMOVED EFFECTIVELY USING EXISTING SNOW REMOVAL EQUIPMENT.

OVERVIEW: THE TEST WILL BE CONDUCTED BY REMOVING SNOW AND ICE FROM THE POWER STRIP USING DIFFERENT COMBINATIONS OF PLOWS AND BRUSHES.

ORGANIZATION: NICK MUSACHIO - TECHNICAL DIRECTOR
JOHN DILLINGHAM - ENGINEERING REVIEW
JOHN FLASCHENRIEM - OBSERVATION
JOHN HARTER - OBSERVATION
CITY MAINTENANCE CREWS - OBSERVATION

MEASURES OF EFFECTIVENESS: SEE DATA COLLECTION SHEET AND QUESTIONNAIRE

DATA: SEE DATA COLLECTION SHEET AND QUESTIONNAIRE

DESCRIPTIONS:

TEST 2A.
PRECISION PLOW BOTH SIDES OF THE POWER STRIP.
DETERMINE IF POWER STRIP IS FUNCTIONAL ACCORDING TO RESULTS OF TEST 1.

TEST 2B.
PRECISION PLOW USING A BOOTED PLOW SYSTEM.
DETERMINE IF POWER STRIP IS FUNCTIONAL ACCORDING TO RESULTS OF TEST 1.

TEST 2C.
USE BRUSH MECHANISM TO REMOVE SNOW FROM THE POWER STRIP AND THE ROADWAY.
DETERMINE IF POWER STRIP IS FUNCTIONAL ACCORDING TO RESULTS OF TEST 1.

TEST 2D.
USE BOOTED PLOW AND BRUSH MECHANISM TO REMOVE SNOW FROM THE POWER STRIP AND THE ROADWAY.
DETERMINE IF POWER STRIP IS FUNCTIONAL ACCORDING TO RESULTS OF TEST 1.

TIMED LEVEL EFFORT: PERSON/POWER - 4 PEOPLE FOR 4 HOURS
EQUIPMENT - POWER STRIP, PLOW WITH REMOVABLE BOOTS, BRUSH

SCHEDULE: SEE ATTACHED OVERALL SCHEDULE

SAFETY PROCEDURES: OPERATE SNOW REMOVAL EQUIPMENT ON POWER STRIP ONLY WHEN THE POWER IS OFF.
MAINTAIN A MINIMUM DISTANCE OF TEN FEET FROM THE POWER STRIP AT ALL TIMES WHEN THE STRIP IS POWERED.
OBSERVERS MUST REMAIN A MINIMUM OF THIRTY FEET FROM THE BRUSH OR THE PLOW WHEN THEY ARE IN USE.
E-TRAN ROAD POWERED ELECTRIC VEHICLE
SNOW AND ICE TESTS

TEST # 3
PURPOSE: DETERMINE IF SNOW AND ICE CAN BE REMOVED EFFECTIVELY USING EXISTING SNOW REMOVAL EQUIPMENT.

VIEW: THE TEST WILL BE CONDUCTED USING A FULL SIZE PLOW ON THE POWER STRIP.

ORGANIZATION: NICK MUSACHIO - TECHNICAL DIRECTOR
               JOHN DILLINGHAM - ENGINEERING REVIEW
               JOHN FLASCHENRIEM - OBSERVATION
               JOHN HARPER - OBSERVATION
               CITY MAINTENANCE CREWS - OBSERVATION

MEASURES OF EFFECTIVENESS: SEE DATA COLLECTION SHEET AND QUESTIONNAIRE
DATA: SEE DATA COLLECTION SHEET AND QUESTIONNAIRE
DESCRIPTIONS: ATTEMPT TO REMOVE SNOW AND ICE FROM THE POWER STRIP USING A FULL SIZE PLOW. DETERMINE IF POWER STRIP IS FUNCTIONAL ACCORDING TO RESULTS OF TEST #1.

ESTIMATED LEVEL OF EFFORT: PERSONPOWER - 4 PEOPLE FOR 1 HOUR
EQUIPMENT - POWERSTRIP, FULL SIZE PLOW

SCHEDULE: SEE ATTACHED OVERALL SCHEDULE

SAFETY PROCEDURES: OPERATE SNOW REMOVAL EQUIPMENT ON POWER STRIP ONLY WHEN THE POWER IS OFF.
MAINTAIN A MINIMUM DISTANCE OF TEN FEET FROM THE POWER STRIP AT ALL TIMES WHEN THE STRIP IS POWERED.
OBSERVERS MUST REMAIN A MINIMUM OF THIRTY FEET FROM THE PLOW WHEN IT IS IN USE.
E-TRAN ROAD POWERED ELECTRIC VEHICLE
SNOW AND ICE TESTS

ST # 4

PURPOSE: DETERMINE IF SNOW AND ICE CAN BE REMOVED USING SALT AND/OR CHEMICAL APPLICATIONS.

OVERVIEW: THE TEST WILL BE CONDUCTED BY MELTING SNOW AND ICE FROM THE POWER STRIP USING STANDARD OPERATING PROCEDURES FOR CHEMICAL USAGE.

ORGANIZATION:
NICK MUSACHIO - TECHNICAL DIRECTOR
JOHN DILLINGHAM - ENGINEERING REVIEW
JOHN FLASCHENRIEM - OBSERVATION
JOHN HARPER - OBSERVATION
CITY MAINTENANCE CREWS - OBSERVATION

MEASURES OF EFFECTIVENESS: SEE DATA COLLECTION SHEET AND QUESTIONNAIRE

DATA: SEE DATA COLLECTION SHEET AND QUESTIONNAIRE

DESCRIPTIONS: ATTEMPT TO MELT SNOW AND ICE FROM THE POWER STRIP USING SALT AND/OR OTHER CHEMICALS. DETERMINE IF POWER STRIP IS FUNCTIONAL ACCORDING TO RESULTS OF TEST #1.

ESTIMATED LEVEL OF EFFORT: PERSONPOWER - 4 PEOPLE FOR 3 HOURS
EQUIPMENT - POWERSTRIP, SALT SPREADING VEHICLE

SCHEDULE: SEE ATTACHED OVERALL SCHEDULE

SAFETY PROCEDURES: OPERATE SNOW REMOVAL EQUIPMENT ON POWER STRIP ONLY WHEN THE POWER IS OFF. MAINTAIN A MINIMUM DISTANCE OF TEN FEET FROM THE POWER STRIP AT ALL TIMES WHEN THE STRIP IS POWERED.
OVERVIEW:
THE TEST WILL BE CONDUCTED BY TESTING THE CHOSEN ALTERNATIVE ON THE HUSKY SHUTTLE ROUTE.

ORGANIZATION:
NICK MUSACHIO - TECHNICAL DIRECTOR
JOHN DILLINGHAM - ENGINEERING REVIEW
JOHN FLASCHENRIEM - OBSERVATION
JOHN HARPER - OBSERVATION
CITY MAINTENANCE CREWS - OBSERVATION

MEASURES OF EFFECTIVENESS:
SEE DATA COLLECTION SHEET AND QUESTIONNAIRE

DATA:
SEE DATA COLLECTION SHEET AND QUESTIONNAIRE

DESCRIPTIONS:
ATTEMPT TO REMOVE SNOW AND ICE FROM THE POWER STRIP ON THE HUSKY SHUTTLE ROUTE USING THE CHOSEN ALTERNATIVE. DETERMINE IF POWER STRIP IS FUNCTIONAL ACCORDING TO RESULTS OF TEST #1.

ESTIMATED LEVEL OF EFFORT:
PERSONPOWER - 4 PEOPLE FOR 2 HOURS
EQUIPMENT - POWERSTRIP, APPLICABLE EQUIPMENT CHOSEN FROM EARLIER TESTING

SCHEDULE:
SEE ATTACHED OVERALL SCHEDULE

SAFETY PROCEDURES:
OPERATE SNOW REMOVAL EQUIPMENT ON POWER STRIP ONLY WHEN THE POWER IS OFF.
MAINTAIN A MINIMUM DISTANCE OF TEN FEET FROM THE POWER STRIP AT ALL TIMES WHEN THE STRIP IS POWERED.
## E-TRAN ROAD POWERED ELECTRIC VEHICLE
### DATA COLLECTION SHEET

**DATE:** 3-9-95  
**SITE:** SC TC  
**TIME:** 2:00 PM  
**NAME:** N. Muradzic  
**POSITION:** Tech. Director

<table>
<thead>
<tr>
<th>TEST NUMBER</th>
<th>TEST DESCRIPTION</th>
<th>WEATHER DATA</th>
<th>SNOW DEPTH</th>
<th>OPERABLE</th>
<th>COMMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>1A</td>
<td>COVER POWER STRIP AND ROADWAY SURFACE WITH SNOW.</td>
<td>10°F, 15 MPH, 0&quot;</td>
<td>1&quot;</td>
<td>NO</td>
<td>No. - No contact.</td>
</tr>
<tr>
<td>1B</td>
<td>COVER THE POWER STRIP WITH SNOW.</td>
<td></td>
<td>1&quot;</td>
<td>NO</td>
<td>Partial contact.</td>
</tr>
<tr>
<td>1C</td>
<td>COVER THE POWER STRIP WITH ICE.</td>
<td></td>
<td>1&quot;</td>
<td>NO</td>
<td>No. - No contact.</td>
</tr>
</tbody>
</table>

**SYSTEM**
- **TEMP**: 10°F  
- **WIND**: 15 MPH  
- **DESCR**: 0"  
- **DEPTH**: 1"  
- **OPERABLE**: NO

**COMMENT**
- Solid ice won't stick.  
  - Contacts will not work.
<table>
<thead>
<tr>
<th>TEST NUMBER</th>
<th>TEST DESCRIPTION</th>
<th>WEATHER DATA</th>
<th>SNOW CONDITION DATA</th>
<th>ICE CONDITION DATA</th>
<th>ATTEMPT</th>
<th>SNOW REMOVED</th>
<th>ICE REMOVED</th>
<th>TIME REQUIRED</th>
</tr>
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<tr>
<td></td>
<td></td>
<td>TEMP.</td>
<td>WIND DESCRIPTION</td>
<td>DEPTH</td>
<td>DESCRIP.</td>
<td>FROM STRIP</td>
<td>FROM ROAD</td>
<td></td>
</tr>
<tr>
<td>2A</td>
<td>PRECISION FLOW BOTH SIDES OF STRIP</td>
<td>40°</td>
<td>10</td>
<td>5&quot;</td>
<td>1&quot;</td>
<td>NA</td>
<td>NA</td>
<td>30'-3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2B</td>
<td>PRECISION FLOW USING A ROOLED FLY</td>
<td>0°</td>
<td>10</td>
<td>15&quot;</td>
<td>1&quot;</td>
<td>3</td>
<td>3</td>
<td>30'-24</td>
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<td></td>
</tr>
<tr>
<td>2C</td>
<td>REMOVE SNOW USING BRUSH MECHANISM</td>
<td>0°</td>
<td>10</td>
<td>6&quot;</td>
<td>1&quot;</td>
<td>3</td>
<td>3</td>
<td>30'-24</td>
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</tr>
<tr>
<td>2D</td>
<td>REMOVE SNOW USING BRUSH MECHANISM AND ROOLED FLY</td>
<td>0°</td>
<td>10</td>
<td>15&quot;</td>
<td>1&quot;</td>
<td>3</td>
<td>3</td>
<td>30'-24</td>
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<td></td>
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<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>REMOVE SNOW USING FULL SIZE FLY</td>
<td>0°</td>
<td>15</td>
<td>5.5&quot;</td>
<td>1&quot;</td>
<td>3</td>
<td>3</td>
<td>30'-24</td>
</tr>
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<td></td>
</tr>
<tr>
<td>4</td>
<td>REMOVE SNOW USING CHEMICAL APPLICATIONS</td>
<td>40°</td>
<td>10</td>
<td>2&quot;</td>
<td>2&quot;</td>
<td>5</td>
<td>5</td>
<td>30'-24</td>
</tr>
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</tr>
<tr>
<td>5</td>
<td>TEST CHOOSEN ALTERNATE ON PUBLIC STREET</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1 - CLEAR  2 - SUNNY  3 - LIGHT/DRY  4 - COMPLETE REMOVAL
5 - PARTLY CLOUDY  6 - HEAVY/FOG  7 - SATISFACTORY REMOVAL
8 - OVERCAST  9 - NO REMOVAL  10 - SNOWING  11 - SYSTEM OPERABLE
12 - FROZEN  13 - PARTIAL REMOVAL  14 - SHARPLY OPERABLE
## E-TRAN Road Powered Electric Vehicle Test Questionnaire

### 1. Did the test cause damage to the power strip?

<table>
<thead>
<tr>
<th>Test 2A</th>
<th>Test 2B</th>
<th>Test 2C</th>
<th>Test 2D</th>
<th>Test 3</th>
<th>Test 4</th>
<th>Test 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

- On initial test strip was damaged.
- An initial test chemicals caused problems.
- Brush & blow is chosen method.

### 2. Did the test cause damage to the road maintenance equipment?

<table>
<thead>
<tr>
<th>Test 2A</th>
<th>Test 2B</th>
<th>Test 2C</th>
<th>Test 2D</th>
<th>Test 3</th>
<th>Test 4</th>
<th>Test 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
</tbody>
</table>

### 3. Could there be possible drainage problems associated with this snow and ice removal process?

<table>
<thead>
<tr>
<th>Test 2A</th>
<th>Test 2B</th>
<th>Test 2C</th>
<th>Test 2D</th>
<th>Test 3</th>
<th>Test 4</th>
<th>Test 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yes, if not followed by brush.</td>
<td>Yes, if not followed by brush.</td>
<td>Yes</td>
<td>Brush &amp; Blow works well - No.</td>
<td>Yes. This method makes slippery street.</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

### 4. Is the power strip clean enough to allow the RPEV to function?

<table>
<thead>
<tr>
<th>Test 2A</th>
<th>Test 2B</th>
<th>Test 2C</th>
<th>Test 2D</th>
<th>Test 3</th>
<th>Test 4</th>
<th>Test 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>In light snows.</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

### 5. Do you have any other comments regarding this test?

<table>
<thead>
<tr>
<th>Test 2A</th>
<th>Test 2B</th>
<th>Test 2C</th>
<th>Test 2D</th>
<th>Test 3</th>
<th>Test 4</th>
<th>Test 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Good in conjunction with brush.</td>
<td>Brush &amp; Blow is best.</td>
<td>Works well but should be done soon after snow.</td>
<td>Brush &amp; Blow is a must.</td>
<td>Not is desirable because of electrical reasons - use spri...</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
A COST COMPARISON STUDY
OF THREE ELECTRIC TRANSIT OPTIONS:
E-TRAN Road Powered Electric Vehicles (RPEV), Light Rail Transit (LRT), and Electric Trolley Buses (ETB)

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May, 1995

Submitted to
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This report represents the results of research conducted by the author and does not necessarily represent the views or policy of the Minnesota Department of Transportation.
ACKNOWLEDGMENT

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Many thanks also go to John Harper and David Tripp of the Saint Cloud, MN Metropolitan Transit Commission for their generous assistance with the National Transit Symposium and in compiling this report, and to Jeff Kapsner who contributed to the Electric Trolley Bus section.

FUNDING ACKNOWLEDGMENT

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TABLE OF CONTENTS

I Introduction .......................................................... 1
II Transit Mode Descriptions .......................................... 3
   A. Road Powered Electric Vehicles (RPEV) ...................... 3
   B. Electric Trolley Buses (ETB) ................................ 4
   C. Light Rail Transit (LRT) ....................................... 5
III Methodology .......................................................... 6
IV Transit Mode Evaluation ............................................ 9
V Airport Loop .......................................................... 22
VI Conclusion ........................................................... 24
References ............................................................... 26
Bibliography ............................................................. 28
Appendix: LRT Capital Cost Comparison ............................ 31

LIST OF TABLES

Table 1 Speed Comparisons ........................................... 9
Table 2 E-Tran RPEV Capital Costs Per Mile ....................... 11
Table 3 Other E-Tran RPEV Costs Per Mile ........................ 12
Table 4 Capital Costs Per Mile for Several LRT Systems ........ 13
Table 5 Modified Capital Cost Per Mile: Several LRT Systems . 14
Table 6 Capital Cost Per Mile Summary ............................ 15
Table 7 Operating Costs (ETBs, LRT, Diesel Buses) ............... 16
Table 8 Operating Costs (Cities Without ETBs) ................... 16
Table 9 Safety Comparisons ......................................... 18
Table 10 Electricity or Fuel Cost Per Mile ......................... 21
Summary

This is a cost comparison of E-Tran Road Powered Electric Vehicle (RPEV), Electric Trolley Bus (ETB), and Light Rail Transit (LRT) systems. The study briefly reviews the transit modes, outlines the methodology used, evaluates the three transit modes in accordance with comparison criteria specified in the methodology section, and assesses the suitability of using RPEVs as shuttles connecting the Minneapolis-St. Paul International Airport with rental car parking lots.

Criteria for comparison include speed, accessibility, capacity, frequency of service, capital costs, operating and maintenance costs, ridership and revenue, cost effectiveness, impact on street operation, safety, and environmental concerns. Because this study was limited in scope and did not consider a specific site, many of these criteria could not be specified and it is recommended that they be more fully analyzed when transit options are considered for a specific site. Capital cost criteria include eight specific capital cost components that are applied to the transit modes when the data were available.

This study concludes that the current, automobile-based transit system is untenable in the future and suggests that low-cost options to control congestion and reduce environmental costs such as congestion and automobile taxes be used first before considering the high, capital cost electric transit options. Should ridership expectations warrant it, this study concludes that LRT would be the most expensive system would cost the most, followed by ETB and RPEV systems respectively.

The reader should be cautioned that many of the numbers used in this study represent averages and aggregations that do not refer to a particular site; in this sense they are generic and hide a great deal of system variety. The numbers for E-Tran's RPEV system are only projections and will need adjustment if an actual system is ever built. Since the RPEV system appears to be the lowest cost per mile transit system (though close to ETBs), it seems prudent to fully test the system and see if the cost projections are realistic by building a test track using a full-sized bus. To focus solely on Light Rail vehicles as the electric transit option as regional rail authorities in the Twin Cities have done seems short-sighted in light of new technological development such as the RPEV system.
I. INTRODUCTION

Despite what commercials portray, getting around in a city by automobile is increasingly more problematic. Though automobiles offer significant benefits such as flexibility, speed and comfort, their costs, namely congestion, pollution, costly accidents and poor land use, push policy makers and transit planners to consider other alternatives.

More people are driving more with fewer passengers per automobile in the Twin Cities. The Twin City Metropolitan population increased about 23% per decade between 1949 and 1990 and during this time, "...person trips by all travel modes increased over five-fold...while person trips per capita more than doubled." Additionally, the percentage of people riding buses and the average number of passengers per automobile fell. [15, p.12] While road travel is increasing by annual rates of 2 to 4 per cent%, funds and additional land for roadway improvements are increasingly scarce. [8] More traffic and less road capacity means more congestion, slower trips and lost time.

Further reducing our love affair with the automobile are the air pollution costs, the risks of greenhouse climate change, the costs of securing our oil supply lines, accidents, noise, highway costs, and land lost to parking and roads. The dollar value of these costs run well in the hundreds of billions of dollars annually. [13, 11] In short, the status quo of relying heavily on automobiles for transportation is not a viable one for the future.

Can this status quo be made more efficient without resorting to high capital cost alternatives? Economist Herbert Mohring (University of Minnesota) says yes and suggests a policy of congestion cost pricing and/or automobile taxes such as is being done in Singapore and Hong Kong. Other ways to speed traffic flows involve Intelligent Transportation Systems (ITS), the focus of research at the University of Minnesota's Center for Transportation Studies and the Intelligent Transportation Systems Institute. Combined with an effective bus scheduling system and less polluting vehicles (using alternative fuels or electric motors), this option could extend an automobile-based transportation system a while longer. Experimental technologies such as fuel-cell and hydrogen powered automobiles and buses, and super or "hyper cars" [10] promise much less polluting vehicles for the future. In short, an automobile-based transportation system could be made more efficient with a combination of taxes, better highway management and new technology.
The present political pressure to keep taxes low, however, seems to preclude a substantial reform based on congestion-cost pricing. Though traffic flow improvements have been made to highways, people still want to drive their own cars and urban populations continue to rise. The near-term prognosis for transportation in major American cities is higher congestion costs, more pollution, and a pressing need to invest in alternative, transit options.

To address this need, the Minnesota State Legislature commissioned this study to compare costs between three transit options: Road Powered Electric Vehicles (RPEVs) as developed by E-TRAN, Inc.; Electric Trolley Buses (ETBs); and Light Rail Transit (LRT) for application in the Twin Cities and elsewhere. It also assesses RPEV technology as a replacement for the diesel shuttle buses operating between the terminal and car rental agencies in the Minneapolis-St. Paul International Airport.
II. TRANSIT MODE DESCRIPTIONS

Before proceeding to the methodology and analysis of the above transit modes, it is useful first to briefly describe them.

A. Road Powered Electric Vehicle (RPEV)

1. Definition

The RPEV technology reviewed here is the one E-TRAN, Inc. has developed. It consists of an electric, non-tracked vehicle capable of drawing power from segmented power strips mounted onto a roadway which are switched on and off as a vehicle passes over them. "A power switching device, driven by road embedded vehicle presence sensors switch power on and off to the appropriate strips at the appropriate time." [7, p.ii] An E-TRAN vehicle (automobile or bus) "... can also store electrical energy in a battery onboard the vehicle. The RPEV uses electricity from the battery when it is not in contact with an electrified rail." [7, p.1]

2. Brief History

E-TRAN founders have been developing RPEV technology since 1986 and. E-TRAN was incorporated in 1992, following the construction of models and early prototypes and the first RPEV legislative hearings in 1991-92. E-TRAN was incorporated in 1992. E-TRAN's claim has been that its technology is less polluting than Diesel Buses, cheaper than Light Rail Transit and more attractive than the Electric Trolley Bus. The E-TRAN propulsion concept was tested in 1992 by the University of Minnesota, and a final report issued in 1994 suggested that the technology must address some engineering and safety issues and concluded that it be considered for low mass, low speed applications (such as go-karts).

Determining whether the E-Tran technology is economically viable compared to other electric transit modes is the task of this report. Other reports jointly submitted with this one address engineering and safety issues.
B. Electric Trolley Bus (ETB)

1. Definition

ETBs are conventional buses with an electric motor instead of a diesel engine; they obtain their power from two poles that extend from the top of the bus to overhead wires some 18 feet above the road.

2. Brief History

ETB technology was developed in the 1880's, was first implemented in Germany in 1901, and began its rise in North America in the 1920's. From 1927 to 1950, the trolley bus became the predominant mode of public transport in many of the major American transit systems. It flourished from 1950 to the early 1970's, when, toward the end of this period, the trolley started to disappear. [22, pp. 1-2] Trolley buses currently run in only five American cities: Seattle, San Francisco, Dayton, Boston a. And Philadelphia.

Although the main reason for abandoning trolley buses was that they were more expensive to operate than diesel buses, demographics had a hand in dampening enthusiasm for ETBs. By the late 1950's, private transportation companies had become financially strapped and low-density suburbs could not provide the revenues to offset the high capital costs required to extend or maintain lines.

What of the future? Critics say ETB's are "ugly, inflexible and costly," while supporters praise their "...low exhaust gas emission, low noise levels, high starting power, suitability for hilly terrains, uncomplicated tunnel operation requiring less ventilation, high payload..."and their freedom from diesel fuel. [4, p.8] American cities are committed to their ETB systems and new developments, such as dual-mode buses (electric and diesel) that permit the reduction of the overhead wire network and increase flexibility, make ETBs more attractive.
C. Light Rail Transit (LRT)

1. Definition

LRT is formally defined by the Transportation Research Board's (TRB) Light Rail Transit Committee as a metropolitan electric railway system characterized by its ability to operate single cars or short trains along exclusive rights of way at ground level, on aerial structures, in subways, or occasionally, in streets, and to board and discharge passengers at track or car floor level. [12, p.115]

2. Recent History

After a period of investment in rapid transit, heavy rail" (early 70's), during which light rail had dwindled to seven systems, light rail investment began to flourish. Why? Heavy rail was too costly, provided more capacity than medium-sized regions needed and had high labor costs; freight railroads, meanwhile, had no incentive to run them. LRT provided several improvements, namely, a) shorter trains, b) lower-cost and c) at-grade construction. One person could run an LRT vehicle unlike the crew commuter trains required. [20, p.83]

During the 1980's, established systems were refurbished or extended, and new lines entered into service." Between 1980 and 1993 LRT systems in the United States more than doubled from 7 to 15, and additional service is being considered in many other cities. [12, p.116] New LRT systems are running in 12 North American cities previously without rail (8 in the United States, 2 in Canada, and 2 in Mexico). Two more are under construction [Denver's system is now operational], as are extensions elsewhere. [20, p.83]

Since it was first implemented, LRT has provided urban populations with a fast, environmentally sound (to the extent that pollution is generated outside the city) means of transportation within cities. LRT also comes with significant drawbacks such as high capital costs and fixed guideways which make adjustments extremely costly. However, in a sufficiently densely populated area with well-designed corridors which insure the greatest initial and new ridership, LRT can be successful.
III. METHODOLOGY

The basic assumption of this study is that all vehicles will travel in a dedicated lane on a section of highway (such as a High Occupancy Vehicle lane) and that LRT will operate at grade. This allows us to compare capital and maintenance costs without distractions such as different right-of-way costs and roads that might only allow for one mode of transportation (such as LRT systems with track beds that can only accommodate light rail cars).

It is clear that assuming away things in order to more closely compare "apples with apples also distorts the conclusions if investment decisions consider different-sized vehicles or different right-of-way considerations, but this can be addressed in alternative versions of this report. The scope of this study is already rather broad and assumptions have to be made to make it manageable for the time and expense allocated to it.

Criteria for overall comparisons are based on the analysis done by Parsons De Leuw, Inc.[17] Though these criteria go beyond a simple cost comparison, they include other measures of "cost" and "benefit" that any transit comparison makes; any meaningful comparison, for example, must include environmental considerations. It is for other studies, however, to go into depth to calculate the dollar value of these costs and benefits.

Criteria for comparing capital costs are based on those used by Booz, Allen & Hamilton, Inc. In a study entitled Light Rail Transit Capital Cost Study which will also be issued to assess ETB and RPEV capital cost estimates. Both sets of criteria are explained below.

A. Overall Comparison Criteria

Attempting to compare technologies is a massive undertaking, but it must be done in order to give citizens and policy-makers information on which to base sound decisions. The system operating criteria that seem to best deal with the large amount of disparate information are the De Leuw criteria [17] and they are listed and briefly explained below:

1. Speed: a transit vehicle's speed depends on its technological capability, how it interacts with other transit modes, station spacing, station dwell times, rates of acceleration and deceleration, speed through switches, maximum cruise speed and human factors.

2. Accessibility: This pertains to a) the transit system's accessibility to the population and employment and, b) the relative ease with which disabled people can get on or off the system.
3. **Capacity**: This measure refers to the number of passengers that can be transported by the system.

4. **Frequent Service**: This measures the time between train departures and arrivals.

5. **Capital Cost**: This criterion covers the costs required for an operational transit system and will be explained in more detail below.

6. **Operating and Maintenance Cost**: This includes daily operating costs, such as labor costs and fuel/energy costs, as well as preventative maintenance costs.

7. **Ridership and Revenue**: The revenue obtained by a transit system is equal to the number of riders multiplied by the fare charged. The collected fare, a cost to the rider, is at the same time a measure of transit benefits for which consumers are willing to pay.

8. **Cost Effectiveness**: Cost effectiveness criteria compare projects in a manner that includes both cost and performance. This element shows the project's effectiveness in attracting ridership to its capital and operating cost. "It relates value received, in terms of benefit obtained, to the resources to be invested in each alternative." (14, p.6-14)

9. **Impact on Street Operation**: Is the system capable of mixed traffic?

10. **Safety**: This refers to whether people could be evacuated in an emergency or whether the disabled could find easy access or egress.

11. **Environmental Concerns**: This category includes a variety of concerns ranging from pollution, adverse weather capability, to aesthetics and noise.

**B. Capital Cost Characteristics**

A United States Department of Transportation study performed by the consulting firm of Booz, Allen & Hamilton, Inc. and titled *Light Rail Transit Capital Cost Study*, separated costs into the following eight categories; they constitutinge the framework for comparison used in this study, though the data do not in every instance coincide with these categories.
1. **Guideway Elements.** This includes track and structural requirements along the entire right of way.

2. **Yards and Shops.** This includes cost of buildings, control centers, maintenance shops, etc.

3. **Systems.** This includes costs of signal systems, communications, fare collection equipment, and electrification.

4. **Stations.** This includes at grade, subway and elevated stations. Also includes parking lots, garages, and pedestrian overpasses.

5. **Vehicles.** This includes both revenue and non-revenue (automotive support) vehicles.

6. **Special Conditions.** This includes cost of relocating existing utility lines, demolitions, roadway, changes and environmental mitigation.

7. **Right of Way (ROW).** This includes the cost of land acquisition and related costs (management, appraisal, etc.).

8. **Soft Costs.** This includes all planning, engineering and management costs (e.g., feasibility studies, training/testing, finance charges).

In sum, these two sets of criteria will be applied to the three transit modes, RPEV, ETB, and LRT with the diesel bus/automobile mode currently in place as the no-alternative case. It must be noted that actual operational data will be used to compare diesel bus, LRT, and ETB systems to E-TRAN's model and non-operational RPEV. This makes comparison much more difficult, but as is the case with any emergent technology, the decision to invest in an unproven technology is often made without knowing everything about it. It must also be noted that certain comparative categories were not explicitly called for in the legislative mandate so research on a few of the comparison categories (e.g., Speed, Accessibility, Impact on Street Operations, and Environmental Concerns) will be spotty. Of course, in the case of RPEVs, the information only can be estimated or suggested.
IV. TRANSIT MODE EVALUATION

This section uses the Salt Lake City evaluative criteria to evaluate each mode specified in this report. Since the comparison does not specifically designate a location (e.g., the Central Corridor in Ramsey and Hennepin Counties), this report will not evaluate the site to see what technological requirements are called for. If one knows what transit characteristics the site calls for, then a comparison of transit modes can proceed with more specificity. Instead, this report was not assigned a specific location to study and assumes a generic, designated roadway with equal right of way costs for each transit mode. Specific information about LRT systems in Minneapolis-St. Paul comes from work done on the Central Corridor project.

1. **Speed:** RPEV will be operated at grade and is capable of speeds comparable to ETBs, Diesel buses, and LRT vehicles in an area such as the Central Corridor. Because of the population density in a site such as the Central Corridor and the number of stations, high speeds will not be a major issue. The data in Table 1 are given in miles per hour.

   Table 1: Speed Comparisons (mph)

<table>
<thead>
<tr>
<th>Criterion</th>
<th>RPEV</th>
<th>ETB</th>
<th>LRT</th>
<th>DIESEL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed</td>
<td>-----------------</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High</td>
<td>Boston</td>
<td>13.0</td>
<td>23.3</td>
<td>Salt Lake City</td>
</tr>
<tr>
<td>Low</td>
<td>San Francisco</td>
<td>7.4</td>
<td>8.9</td>
<td>San Francisco</td>
</tr>
<tr>
<td>All Sys Avg.</td>
<td>10.1 (same as ETB)</td>
<td>10.1</td>
<td>14.1</td>
<td>13.36</td>
</tr>
</tbody>
</table>

Source: Cambridge Systematics, Inc.

The data indicate that LRT and diesel bus systems overall are a bit faster than ETBs, and by assumed extension, RPEVs. It should be noted that trolley buses are located in more congested areas and must stop more often, while LRT systems can attain greater speeds on line segments with fewer stations. The data are very aggregated and include systems with different grades and different route characteristics so this comparison is not definitive.
2. **Accessibility:** Each transit mode would be built in a congested area with high ridership potential (e.g., the Central Corridor). This means that the number of households and jobs within walking distance (0.25 mile) would be high (determinable by survey). It is also assumed that each mode is at grade and provides vehicles with easy entry and egress for handicapped individuals. Where there are grade changes, this study assumes that all modes would incur similar costs to provide compliance with American Disabilities Act legislation.

3. **Capacity:** This study recognizes that LRT has the largest capacity per vehicle followed by ETB and motor buses respectively, though the difference between motor buses and ETBs is not great. [21]

   According to information about the Denver and St. Louis LRT systems, the standard LRT vehicle has a capacity of 125 passengers with "crush" capacity at peak times of about 200. Average seating capacity, according to American Public Transit Association (APTA) figures, is 59.1 passengers. Additionally, LRT vehicles can be connected to form trains, further increasing the capacity per trip.

   The average seating capacity for ETBs is 53.8 (and by extension, RPEV), while for motor buses it is 43.7. Crush capacity is larger, but does not approach that of LRT vehicles. [21]

   It is assumed that all three transit modes have vehicle capacities appropriate for a chosen site's transit needs.

4. **Service Frequency:** This criterion is measured in terms of headway, or the time between the departure of one train and the arrival of the next. This study assumes that all four modes are capable of headways of three minutes or less (an assumption the Salt Lake City study makes) at peak times. This is important to the passenger in that it conditions how beneficial public transit is and consequently how much the passenger is willing to pay for service. Three minute or less headway is assumed to be acceptable to the riding public.

5. **Capital Cost:** This is probably one of the most important of the comparative criteria used in this study. Any different technology will need to be worth the additional dollars invested in its infrastructure (beyond what we invest in roadways today). The three modes are analyzed separately (diesel buses are mentioned only as the low capital cost option) below.
A. E-TRAN RPEV System

Since an E-TRAN RPEV system has not been built, it is rather difficult to estimate how much such a system would cost. Estimation of capital costs have been compiled by Nick Musachio (E-TRAN founder) in conjunction with William Lindberg of Peoples' Electric Contracting Firm and William Thiesse of Erickson Ellison and Associates. Based on a one-mile installation, RPEV estimated capital costs per mile in 1995 dollars are as follow:

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Low Estimate</th>
<th>High Estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hardware</td>
<td>$58,080</td>
<td>$306,240</td>
</tr>
<tr>
<td>Installation</td>
<td>$585,000</td>
<td>$1,152,000</td>
</tr>
<tr>
<td>Total</td>
<td>$643,080</td>
<td>$1,458,240</td>
</tr>
</tbody>
</table>

In order to make RPEVs comparable with other electric transit modes, other capital costs must be included. Since no RPEV system has been built, it is assumed that an ETB system provides some measure of comparable costs for the purposes of this study. It should be stressed that there is little basis for making this assumption and that no E-TRAN RPEV system has been proven to meet the safety and operational requirements of a real world application. One could argue, for example, that the power delivery component of ETBs would be much cheaper, because it does not need the durability to withstand snowplows nor does it need the elaborate safety features proposed for the RPEV system. Taking this uncertainty into account, one must nonetheless attempt some sort of cost estimate.

Numbers used in Table 3 come from a 1995 Boston study proposing an ETB service expansion. [25] That study assumed an extension of service of 5.4 miles with no right of way costs or other cost categories other than those comprising the actual system. The following table adds other ETB costs on a per mile basis that need to be added to the RPEV total.
Table 3: Other E-TRAN RPEV Costs Per Mile

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Low Estimate</th>
<th>High Estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicles (12 @ $757,000 to $1,000,000 each)</td>
<td>$1,682,222</td>
<td>$2,222,222</td>
</tr>
<tr>
<td>Substation</td>
<td>$648,148</td>
<td>$648,148</td>
</tr>
<tr>
<td>Station/Stops (12 @ $80-$100,000 each)</td>
<td>$177,778</td>
<td>$177,778</td>
</tr>
<tr>
<td>Carhouse Requirements</td>
<td>$2,314,815</td>
<td>$2,314,815</td>
</tr>
<tr>
<td>Subtotal</td>
<td>$4,822,963</td>
<td>$5,362,963</td>
</tr>
<tr>
<td>Total (includes Table 2 totals)</td>
<td>$5,466,043</td>
<td>$6,821,203</td>
</tr>
</tbody>
</table>

If one adds an additional 15% contingency as the Boston study does, the low cost estimate rises to **$6.3 million per mile** and the high estimate rises to **$7.8 million per mile**. Other site-specific costs, such as landscaping and the like would need further specification.

It must be underscored that the above costs relate to ETBs and very likely show substantial underestimation when associated with RPEVs. **Only a rigorous, site-specific study, based on extensive performance testing can better substantiate these capital cost estimates. They are only to give an order of magnitude of RPEV costs.**

B. ETB System

Currently the trolley bus runs in only five American cities: Seattle, San Francisco, Dayton, Boston, and Philadelphia and plans to introduce ETBs in Sacramento, New York City, and Los Angeles have been delayed or eliminated.[5]

According to the 1981 Sanders and Thomas, Inc. Light Rail Transit Feasibility Study for the Twin Cities, trolley bus capital costs per mile were estimated to be $455,000 in 1980 dollars based on construction costs in Seattle and San Francisco. Added to these costs were vehicle costs of $871,000 per mile (based on the 9.46 mile University alignment and an $8.24 million total) and vehicle maintenance and overhaul facilities of $262,000 per mile ($2.48 million X 9.46). The total figure per mile came to $1.59 million 1980 dollars. Not only is this a very old capital cost estimation, but it also does not appear to include special costs attendant to construction or right of way costs. Nevertheless, it specifically analyzes ETB investment in the Twin Cities.
More recent capital cost estimates are drawn from a recent Boston expansion proposal. Based on the April 4, 1995 Washington Street Replacement Service Review, constructing an ETB system would cost between $51.1 million and $53.6 million in 1995 dollars. This translates to a cost per mile range of between $9.5 and $9.9 million. As with the LRT proposal in Boston, the life-cycle of the ETB improvements is assumed to be twenty years.

C. Light Rail Systems

It should be noted that any comparisons of capital costs must be viewed with skepticism. Cities noted in Table 4 not only face different physical characteristics, but they also have employed different basic design philosophies. For example, the data below show that guideway element costs differ significantly "...which illustrates the extensive cost variation from a mainly single track at-grade alignment to the more sophisticated, higher service volume systems that include mainly grade separated and some subway alignment." [2, p.19] The percentage of total project costs differed substantially as well. Guideway costs accounted for 38.3% of total project costs in Portland with more elevated guideways to 17.0% of total project costs in Los Angeles. In addition to different basic design philosophies, several systems have encountered deficiencies that have been rectified through additional capital investment so that the capital cost figures below do not represent the "full" costs of systems in place today (conversation with Ken Stevens, Regional Transit Board). In short, differing "basic design philosophy" as well as site characteristics and post-initial phase experience differed among these systems, making comparison between these cities difficult. At best, these data give a sense of the order of magnitude of capital costs.

The following table (Minneapolis-St. Paul is in 1993 dollars while the other cities are in 1990 dollars) show capital costs per route mile for various LRT systems built since the 1980s.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Mpls/St Paul</th>
<th>Portland</th>
<th>Sacramento</th>
<th>San Jose</th>
<th>Pittsburgh</th>
<th>Los Angeles</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Guideway Elements</td>
<td>10,905</td>
<td>7,013</td>
<td>2,618</td>
<td>2,819</td>
<td>3,016</td>
<td>5,980</td>
<td>4,289</td>
</tr>
<tr>
<td>Yards and Shops</td>
<td>2,367</td>
<td>879</td>
<td>223</td>
<td>948</td>
<td>1,042</td>
<td>1,777</td>
<td>974</td>
</tr>
<tr>
<td>Systems</td>
<td>6,643</td>
<td>1,567</td>
<td>1,095</td>
<td>1,332</td>
<td>1,608</td>
<td>4,634</td>
<td>2,047</td>
</tr>
<tr>
<td>Stations</td>
<td>4,254</td>
<td>1,111</td>
<td>576</td>
<td>200</td>
<td>936</td>
<td>2,649</td>
<td>1,094</td>
</tr>
<tr>
<td>Vehicles</td>
<td>4,625</td>
<td>2,187</td>
<td>1,905</td>
<td>2,600</td>
<td>1,567</td>
<td>3,214</td>
<td>2,295</td>
</tr>
<tr>
<td>Special Conditions</td>
<td>1,485</td>
<td>1,118</td>
<td>979</td>
<td>2,480</td>
<td>604</td>
<td>2,417</td>
<td>1,520</td>
</tr>
<tr>
<td>Right of Way</td>
<td>6,388</td>
<td>4,283</td>
<td>2,196</td>
<td>6,072</td>
<td>6,136</td>
<td>9,221</td>
<td>5,581</td>
</tr>
<tr>
<td>Soft Costs</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TOTAL</td>
<td>36,667</td>
<td>18,585</td>
<td>10,277</td>
<td>16,827</td>
<td>15,185</td>
<td>36,558</td>
<td>19,486</td>
</tr>
</tbody>
</table>

Sources: Mpls/St. Paul data come from the 1993 Central Corridor Summary Document and data about other systems come from Table 2-15 of the September, 1992 "Characteristics of Urban Transportation Systems" published by the Federal Transit Administration, U.S. Department of Transportation.
The numbers above are based on estimated capital costs for the Mpls-St. Paul Corridor and actual capital costs for LRT systems in other cities (total costs are shown in Appendix A). The "average" figure does not include the proposed Minneapolis-St. Paul LRT plan for the Central Corridor. Other systems have been included to give the reader a sense of what LRT systems cost on average in order to judge whether Minneapolis-St. Paul costs seem high or low.

An important methodological note needs to be stressed here. Comparing numbers in 1993 dollars with numbers in 1990 dollars is inappropriate. A more appropriate method is to use Means Construction Cost indices as well as City Cost indices to deflate current data and make them comparable to 1990 data. These were not available for this report so the numbers remain as they were found. Using the Consumer Price Index for all urban consumers (CPI-U) may help some, but it is a price index more appropriate to consumers than to transit investments.

Table 5 below looks at capital costs per mile without special conditions costs, right of way costs and soft costs in order to make these data comparable to RPEV and ETB data. Again, Twin Cities data are in 1993 dollars while the rest are in 1990 dollars.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Mpls/St Paul</th>
<th>Portland</th>
<th>Sacramento</th>
<th>San Jose</th>
<th>Pittsburgh</th>
<th>Los Angeles</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Guideway Elements</td>
<td>10,905</td>
<td>7,013</td>
<td>2,618</td>
<td>2,819</td>
<td>3,016</td>
<td>5,980</td>
<td>4,289</td>
</tr>
<tr>
<td>Yards and Shops</td>
<td>2,367</td>
<td>879</td>
<td>223</td>
<td>948</td>
<td>1,042</td>
<td>1,777</td>
<td>974</td>
</tr>
<tr>
<td>Systems</td>
<td>6,643</td>
<td>1,567</td>
<td>1,095</td>
<td>1,332</td>
<td>1,608</td>
<td>4,634</td>
<td>2,047</td>
</tr>
<tr>
<td>Stations</td>
<td>4,254</td>
<td>1,111</td>
<td>576</td>
<td>200</td>
<td>936</td>
<td>2,649</td>
<td>1,094</td>
</tr>
<tr>
<td>Vehicles</td>
<td>4,625</td>
<td>2,187</td>
<td>1,905</td>
<td>2,600</td>
<td>1,567</td>
<td>3,214</td>
<td>2,295</td>
</tr>
<tr>
<td>TOTAL</td>
<td>28,794</td>
<td>12,757</td>
<td>6,417</td>
<td>7,899</td>
<td>8,169</td>
<td>18,254</td>
<td>10,699</td>
</tr>
</tbody>
</table>

Sources: Mpls/St. Paul data come from the 1993 Central Corridor Summary Document and data about other systems come from Table 2-15 of the September, 1992 "Characteristics of Urban Transportation Systems" published by the Federal Transit Administration, U.S. Department of Transportation. The above numbers ignore special conditions, right of way costs, and soft costs.

If we eliminate all but the above capital cost criteria in order to compare LRT with RPEV, the per mile capital cost for the proposed Minneapolis-St. Paul LRT Central Corridor is about $28.8 million per mile (in 1993 dollars) and represents the costliest project among those compared. If we simply increase the number by a modest inflation rate of 4% per year, the project could cost about $31 million per mile.
The Boston Washington Street expansion represents a more recent LRT proposal. The capital cost in 1995 dollars for a 5.4 mile Light Rail line ranged from $74,100,000 to $105,200,000 which breaks down to $13.7 to $19.5 million per mile. Costs such as right of way expenditures are not included. The life cycle of the LRT system improvement is assumed to be 20 years.

D. Diesel Bus Capital Costs

Since a diesel bus system readily can use the roadways in place and does not need any equipment to access a power source other than a motor, it has the lowest capital cost requirement compared to LRT, ETB and RPEV.

Each bus costs approximately $230,000, though it must be noted that diesel buses only have a minimum useful life of 12 years, versus trolley buses (and by extension RPEVs) and LRT vehicles that last an average of 25 years. In addition to vehicle costs, there are also yards and shops that must be built for vehicle maintenance and storage.

E. Summary: Capital Cost

The following table shows capital costs in millions of 1995 dollars per mile for all three modes in this comparison. The numbers do not include right of way, special, or soft costs. Diesel buses are assumed to be the least expensive option.

<table>
<thead>
<tr>
<th>Criterion</th>
<th>RPEV System</th>
<th>ETB System</th>
<th>LRT System</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capital Costs</td>
<td>$6.3 - $7.8*</td>
<td>$9.5 - $9.9</td>
<td>$14 - $31</td>
</tr>
</tbody>
</table>

*This is a very rough guess and could well exceed ETB costs if a system is actually built.

These numbers only give a rough, indicative cost for these systems and show that LRT is the most expensive while ETB systems may be more expensive than an RPEV system. Actual construction in a specific site will change the actual amount (especially with the RPEV system since none has ever been built).
6. **Operating and Maintenance Costs:**

Table 7: Operating Costs (ETB, LRT, Diesel Buses)

<table>
<thead>
<tr>
<th>City</th>
<th>Mode</th>
<th>cost/pas/trp</th>
<th>cost/pas/mi</th>
<th>cost/rev/mi</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boston, MA</td>
<td>ETB</td>
<td>2.31</td>
<td>1.01</td>
<td>9.94</td>
</tr>
<tr>
<td></td>
<td>LRT</td>
<td>1.01</td>
<td>0.72</td>
<td>16.61</td>
</tr>
<tr>
<td></td>
<td>Diesel</td>
<td>2.06</td>
<td>0.9</td>
<td>8.63</td>
</tr>
<tr>
<td>Dayton, OH</td>
<td>ETB</td>
<td>2.4</td>
<td>0.91</td>
<td>5.93</td>
</tr>
<tr>
<td></td>
<td>Diesel</td>
<td>2.67</td>
<td>0.64</td>
<td>4.07</td>
</tr>
<tr>
<td>Philadelphia, PA</td>
<td>ETB</td>
<td>1.23</td>
<td>0.73</td>
<td>10.17</td>
</tr>
<tr>
<td></td>
<td>LRT</td>
<td>1.37</td>
<td>0.6</td>
<td>13.65</td>
</tr>
<tr>
<td></td>
<td>Diesel</td>
<td>1.61</td>
<td>0.58</td>
<td>7.65</td>
</tr>
<tr>
<td>San Francisco, CA</td>
<td>ETB</td>
<td>0.78</td>
<td>0.54</td>
<td>9.23</td>
</tr>
<tr>
<td></td>
<td>LRT</td>
<td>1.6</td>
<td>0.59</td>
<td>16.01</td>
</tr>
<tr>
<td></td>
<td>Diesel</td>
<td>1.13</td>
<td>0.95</td>
<td>8.99</td>
</tr>
<tr>
<td>Seattle, WA</td>
<td>ETB</td>
<td>1.35</td>
<td>0.71</td>
<td>9.65</td>
</tr>
<tr>
<td></td>
<td>LRT</td>
<td>6.83</td>
<td>6.88</td>
<td>26.52</td>
</tr>
<tr>
<td></td>
<td>Diesel</td>
<td>2.92</td>
<td>0.44</td>
<td>6.50</td>
</tr>
<tr>
<td>Averages</td>
<td>ETB</td>
<td>0.99</td>
<td>0.63</td>
<td>9.24</td>
</tr>
<tr>
<td></td>
<td>LRT</td>
<td>1.38</td>
<td>0.62</td>
<td>15.14</td>
</tr>
<tr>
<td></td>
<td>Diesel</td>
<td>1.79</td>
<td>0.63</td>
<td>7.48</td>
</tr>
</tbody>
</table>

Sources: FY 1992 Section 15 data and APTA 1994 Transit Passenger Vehicle Fleet Inventory

The table above indicates operating and maintenance costs for cities that have ETB, LRT and Diesel bus systems.

The following table shows operating costs for other cities that have only LRT and Diesel Bus systems; averages for all systems are given at the bottom of this table.

Table 8: Operating Costs (Cities without ETBs) dollars/mile

<table>
<thead>
<tr>
<th>City</th>
<th>Mode</th>
<th>cost/pas/trp</th>
<th>cost/pas/mi</th>
<th>cost/rev/mi</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baltimore, MD</td>
<td>LRT</td>
<td>13.52</td>
<td>1.59</td>
<td>0.86</td>
</tr>
<tr>
<td></td>
<td>Diesel</td>
<td>1.51</td>
<td>0.48</td>
<td>0.06</td>
</tr>
<tr>
<td>Buffalo, NY</td>
<td>LRT</td>
<td>1.42</td>
<td>0.63</td>
<td>1.49</td>
</tr>
<tr>
<td></td>
<td>Diesel</td>
<td>1.85</td>
<td>0.58</td>
<td>0.23</td>
</tr>
<tr>
<td>Cleveland, OH</td>
<td>LRT</td>
<td>2.16</td>
<td>0.35</td>
<td>1.35</td>
</tr>
<tr>
<td></td>
<td>Diesel</td>
<td>2.56</td>
<td>0.72</td>
<td>0.22</td>
</tr>
<tr>
<td>Los Angeles, CA</td>
<td>LRT</td>
<td>3.64</td>
<td>0.4</td>
<td>1.33</td>
</tr>
<tr>
<td></td>
<td>Diesel</td>
<td>1.48</td>
<td>0.39</td>
<td>0.24</td>
</tr>
<tr>
<td>New Orleans, LA</td>
<td>LRT</td>
<td>0.77</td>
<td>0.36</td>
<td>0.55</td>
</tr>
<tr>
<td></td>
<td>Diesel</td>
<td>1.17</td>
<td>0.6</td>
<td>0.27</td>
</tr>
<tr>
<td>Newark, NJ</td>
<td>LRT</td>
<td>1.41</td>
<td>0.43</td>
<td>0.75</td>
</tr>
<tr>
<td></td>
<td>Diesel</td>
<td>3.31</td>
<td>0.52</td>
<td>0.24</td>
</tr>
<tr>
<td>Pittsburgh, PA</td>
<td>LRT</td>
<td>2.69</td>
<td>0.47</td>
<td>1.42</td>
</tr>
<tr>
<td></td>
<td>Diesel</td>
<td>1.93</td>
<td>0.55</td>
<td>0.27</td>
</tr>
<tr>
<td>Portland, OR</td>
<td>LRT</td>
<td>1.49</td>
<td>0.28</td>
<td>0.59</td>
</tr>
<tr>
<td></td>
<td>Diesel</td>
<td>1.6</td>
<td>0.48</td>
<td>0.17</td>
</tr>
<tr>
<td>Sacramento, CA</td>
<td>LRT</td>
<td>1.67</td>
<td>0.34</td>
<td>0.97</td>
</tr>
<tr>
<td></td>
<td>Diesel</td>
<td>2.4</td>
<td>0.6</td>
<td>0.23</td>
</tr>
<tr>
<td>San Diego, CA</td>
<td>LRT</td>
<td>1.1</td>
<td>0.16</td>
<td>0.62</td>
</tr>
<tr>
<td></td>
<td>Diesel</td>
<td>2.39</td>
<td>0.34</td>
<td>0.17</td>
</tr>
<tr>
<td>San Jose, CA</td>
<td>LRT</td>
<td>3.13</td>
<td>1.72</td>
<td>0.89</td>
</tr>
<tr>
<td></td>
<td>Diesel</td>
<td>3.23</td>
<td>0.8</td>
<td>0.21</td>
</tr>
<tr>
<td>Averages for all Systems</td>
<td>ETB</td>
<td>0.99</td>
<td>0.63</td>
<td>0.28</td>
</tr>
<tr>
<td></td>
<td>LRT</td>
<td>1.64</td>
<td>0.46</td>
<td>0.94</td>
</tr>
<tr>
<td></td>
<td>Diesel</td>
<td>1.86</td>
<td>0.52</td>
<td>0.21</td>
</tr>
</tbody>
</table>
According to these data, operating costs, when compared to transit systems that had included Diesel Buses, ETBs and LRT Vehicles, the cost per passenger mile was nearly identical. Though this operating cost measure may favor LRT vehicles since LRT passengers travel farther per trip in vehicles with larger capacity, it seemed the better measure to use to compare all three modes, since it apportions cost to each passenger and put all three modes on a somewhat even field.

The cost per passenger trip measure of operating efficiency indicated that Diesel Buses were most expensive to operate, while ETBs were the least costly. The reason for this is that trolley buses are located in more densely-populated urban areas and take passengers on trips that are relatively short.

The cost per revenue mile indicator shows diesel buses to be the least expensive to operate. Since diesel buses travel longer distances on average than ETBs and LRT vehicles and are larger systems, the revenue base into which costs can be divided is much larger.

When compared to all other systems (which includes many non-ETB using cities), ETBs came out on top when considering each passenger trip (same as we saw above), LRTs were superior when considering cost per passenger mile, and Diesel Buses were cheaper to operate when considering cost per revenue mile (same as above). This study has no information about RPEVs, so a comparison can not be made.

In sum, when considering costs per passenger mile as the criterion by which we can best compare operating cost efficiency, then one can conclude that LRT vehicles are more inexpensive to operate when considering all systems. If one only compares the systems that contain all three transit modes, then all three modes have somewhat equal operating costs. As with any numbers in this study, one has to have a clear idea of what the transit mode is designed to do, and have a solid grasp of ridership data, before one can say which mode is cheaper to operate for a specific site.

g. Ridership and Revenue: This is determined by the site and since this study is generic, this category cannot be determined. If the Central Corridor is used, then ridership predictions for that location ought to be used. The Husky Shuttle in St. Cloud also has a high ridership potential and can be measured if that site is used. Revenue depends on ridership and a chosen fare structure; since this study has no specific site, this comparative criterion cannot be addressed.

It was noted in two studies [18, 15] and in a presentation by H. Mohring, that predictions of increased ridership resulting from investment in LRT or other systems are usually overstated.
and do not cover operating costs much less the debt service on invested capital. The Pickrell study, for example, indicates that forecasted costs per ride versus actual costs per ride differed substantially. As Mohring stated at the National Transit Symposium at St. John's (October, 1994) "Seven of these projects [LRT and Heavy Rail Projects] provide both predicted and actual costs per ride. The weighted average prediction was $2.35 while the weighted-average actual cost was $8.56, almost three times the prediction."

Any further investigation of a high capital transit mode needs to do a careful analysis of projected ridership...especially of increased ridership owing to the new transit mode.

h. Cost Effectiveness: The cost-effectiveness calculation required by the Federal Transit Administration and calculated in the form of an index, provides a measure of the relative attractiveness of various transit alternatives. The cost-effectiveness calculation considers both operating and capital costs associated with the average life of each element.

Since this criterion considers capital and operating costs of particular projects in specific sites that elicit specific new ridership (e.g., cost per new transit trip, and cost per rail passenger), a cost-effectiveness study is beyond the scope of this study. It must be noted that the 1993 Central Corridor study estimated that the cost-effectiveness index for LRT was $34.14 per new rider and, for a Busway, it was $29.15.

i. Impact On Street Operation: This study assumes that all modes have about the same impact on street operations. Since there is no specific site, the study cannot make any determinations about street operations. We can say, however, that dedicated lanes in crowded cities probably will not lead to less congestion.

j. Safety: The following table indicates that LRT, ETB, and Diesel buses have a reputation for safety.

Table 9: Safety Comparisons

<table>
<thead>
<tr>
<th>Criterion</th>
<th>LRT</th>
<th>ETB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Incidents per vehicle</td>
<td>High .44 Boston</td>
<td>.07 San Francisco</td>
</tr>
<tr>
<td>revenue mile</td>
<td>Low .01 Los Angeles</td>
<td>.03 Seattle</td>
</tr>
<tr>
<td></td>
<td>Avg .07</td>
<td>0.06</td>
</tr>
<tr>
<td>Injuries per vehicle</td>
<td>High .71 Cleveland</td>
<td>.08 Philadelphia</td>
</tr>
<tr>
<td>revenue mile</td>
<td>Low .00 Pittsburgh</td>
<td>.01 Boston</td>
</tr>
<tr>
<td></td>
<td>Avg 0.1</td>
<td>0.05</td>
</tr>
</tbody>
</table>

Source: St. Cloud MTC
The data seem to indicate that ETB is safer than LRT, but it must be recognized that there are fewer and more limited trolley systems operating than are LRT systems and Diesel systems. RPEV systems may show a record similar to ETBs though there are no data to substantiate this.

k. Environmental Concerns: This analysis in this section will focus on the impacts all four modes have on the atmosphere, aesthetic sense, hearing, and how vulnerable these modes are to extreme weather conditions.

1) Air Pollution: The primary benefit associated with ETB, LRT, and RPEV transit modes is that they do not directly pollute the air where they are used, whereas diesel buses and automobiles do. The scope of this study did not include quantifying the avoided health costs that electric transit can count as a benefit. Any study comparing transit modes in a specific alignment should estimate the benefits of reduced pollution in a congested area.

A 1981 Metropolitan Transit Commission study [1] comparing ETBs with motor buses shows ETB pollutants to be primarily sulfur oxides (SOx) and oxides of nitrogen (NOx), which result from burning coal to produce electricity. Diesel bus pollutants are mostly carbon monoxide (CO), nitrogen oxides (NOx), hydrocarbons (HC), and particulates (TSP). The study concluded that ETBs are "...generally less polluting than are diesel coaches." [1, p. 48] Further, it can be argued that pollutants can be better controlled at a utility's smoke stack than at the end of a vehicle's tailpipe. This study assumes that LRT vehicles, because they use more electricity, will cause more regional or airshed pollution (utilities), but help local air quality on the street.

Even if a city opts for diesel buses, they still pollute less than the equivalent number of automobiles needed to transport the same number of passengers. It is estimated that one bus carrying 36 passengers to work and back uses 10 times less energy than if those passengers traveled in their own automobiles. (Minnesota Department of Public Service Energy Division)

RPEVs are assumed to provide the same pollution reduction benefits ETBs provide. Calls to the Pollution Control Agency and the regional Environmental Protection Agency offices elicited few concrete responses usable in this study and more specific information will require further study.

2) Noise Pollution: RPEVs, ETBs and LRT vehicles are less noisy than diesel buses. In a 1993 Seattle environmental impact study, the peak acceleration noise generated by a diesel bus was measured to be between 80 and 83 Decibels Adjusted (dBA). In the same study, the ETB
measured between 70 and 73 dBA. This 9-10 dBA difference also was recorded during a hill climb at 30 miles per hour. This noise reduction is more of a benefit in residential areas than in city streets, though for a route such as the Husky Shuttle in St. Cloud, where buses run on moderately congested streets, this benefit could be significant.

The 1981 Sanders and Thomas study notes in its summary that "noise pollution from LRT is less than noise pollution from most other modes and can be screened." [19, p. VIII-4] The other modes include ETBs and diesel buses.

3) Visual-Aesthetic Concerns: All the literature reviewed noted that ETB overhead wires were a major aesthetic concern for cities considering a new system, but that once in place, people did not overly concern themselves with the wires.

The ETB's contact wires raise aesthetic concerns, but they could be placed strategically above sidewalks or close to tall buildings and trees in order to minimize their impact, such as has been done in Dayton, Ohio. The span wires, which are either attached to poles or adjacent buildings, are relatively unobtrusive when supporting straight contact wires, but around corners and switches, they become an eyesore. A limited, dual-powered bus with the ability to make turns wire-free could eliminate some of this excess wire and the attendant visual pollution. LRT tracks and wires have not been evaluated.

As we know, beauty is in the eye of the beholder and one could find RPEV pantographs and powerstrips, or the LRT tracks in the road unattractive; certainly bike riders would not appreciate tracks in the road. Any more precise way to value the visual effects or pollution needs more exacting surveying which is beyond the scope of this report.

4) Energy Efficiency: The 1981 Twin Cities Trolley Feasibility study noted that by assuming that 1 kilo watt hour (kwh) requires 0.072 gallons of low sulfur fuel, and a trolley fleet based on chopper control (which increases energy efficiency), a trolley fleet "...could improve on current [diesel bus] fleet fuel economy." [1, p.46] The data on the next page (Table 10) indicate that diesel and ETB transit modes have the same electricity or fuel cost per passenger mile, and are only marginally less expensive than LRT vehicles. When measuring electricity or fuel costs per revenue mile, diesel buses are less expensive than ETBs and LRT vehicles are more energy costly than the other two modes. Again, RPEVs are assumed to be as energy efficient as ETBs.
Further, if all other systems are included, the electricity or fuel costs per revenue mile rise to $0.93 for LRT vehicles, stay the same at $0.28 for ETBs and decrease to $0.21 for diesel buses. The electricity or fuel cost per passenger mile stays essentially the same (LRT costs rise to $0.04).

It appears from these numbers that there are no fuel savings that would offset the high, initial capital costs incurred with electric transit. A significant national benefit enjoyed by electric transit, however, is that the U.S. would be less dependent on foreign oil by using electric transit. Given the high cost of protecting foreign oil supplies (e.g., Operation Desert Storm) petroleum-powered transit is more expensive than it initially appears.

Table 10: Electricity of Fuel Cost Per Mile
(Systems with ETBs)

<table>
<thead>
<tr>
<th>City</th>
<th>Mode</th>
<th>Elec/fuel cost/rev mile</th>
<th>Elec/fuel cost/pass mile</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boston</td>
<td>ETB</td>
<td>0.27</td>
<td>0.03</td>
</tr>
<tr>
<td></td>
<td>LRT</td>
<td>1.43</td>
<td>0.06</td>
</tr>
<tr>
<td></td>
<td>Diesel</td>
<td>0.23</td>
<td>0.02</td>
</tr>
<tr>
<td>Dayton, OH</td>
<td>ETB</td>
<td>0.37</td>
<td>0.06</td>
</tr>
<tr>
<td></td>
<td>Diesel</td>
<td>0.21</td>
<td>0.03</td>
</tr>
<tr>
<td>Philadelphia, PA</td>
<td>ETB</td>
<td>0.76</td>
<td>0.05</td>
</tr>
<tr>
<td></td>
<td>LRT</td>
<td>1.13</td>
<td>0.05</td>
</tr>
<tr>
<td></td>
<td>Diesel</td>
<td>0.28</td>
<td>0.02</td>
</tr>
<tr>
<td>San Francisco, CA</td>
<td>ETB</td>
<td>0.17</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td>LRT</td>
<td>0.35</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td>Diesel</td>
<td>0.31</td>
<td>0.03</td>
</tr>
<tr>
<td>Seattle, WA</td>
<td>ETB</td>
<td>0.32</td>
<td>0.02</td>
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<tr>
<td></td>
<td>LRT</td>
<td>0.53</td>
<td>0.14</td>
</tr>
<tr>
<td></td>
<td>Diesel</td>
<td>0.23</td>
<td>0.02</td>
</tr>
<tr>
<td>Averages</td>
<td>ETB</td>
<td>0.28</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>LRT</td>
<td>0.82</td>
<td>0.03</td>
</tr>
<tr>
<td></td>
<td>Diesel</td>
<td>0.26</td>
<td>0.02</td>
</tr>
</tbody>
</table>

Sources: FY 1992 Section 15 data and APTA 1994 Transit Passenger Vehicle Fleet Inventory

5) Land Use Impacts: Zoning laws that reduce "leap-frog" development and slow development that builds low-density housing on fertile, agricultural land could be coupled with electric transit routing to slow city and suburban expansion. This has the effect of reducing energy used in transportation and housing by making cities more compact. This also has the effect of making land more expensive for the homebuyer and business owner. This study goes no further into this issue except to note that citizens need to decide what sort of cities and land use patterns they want and which transit mode is more compatible with that pattern.
V AIRPORT LOOP

Part of the legislative mandate for this study was to consider replacing the current rental car shuttle at the Minneapolis-St. Paul International Airport with RPEVs.

According to John Harper (intern at the St. Cloud MTC and major source for this section), the present rental car shuttle system in operation at the airport consists of a loop, 930 feet in each direction, connecting the main terminal to the rental car facilities beyond the parking ramps. Because of the constraints of the terminal end cul de sac, three Superbuses and one Carpenter 35 foot bus are used for this service. A maximum of three buses are used during peak times. The weekly passenger trips for 1993-94 reached a maximum of 50,000, with many weeks exceeding 40,000 passengers. The peak hourly rate is approximately 900 trips. [6, p.1]

According to Greg Leean, Manager of Landside Operations of the Metropolitan Airports Commission (MAC), two major difficulties exist with the current at-grade shuttle system. First, the current system is reaching capacity constraints. In a letter to John Harper dated February 16, 1995, Greg Leean states that "[t]he final figures for 1994 indicate that we handled 1,912,000 passengers on this system. At times, the peak load was beyond the capacity of the system which created the need to leave people behind at either end of the route during various times of the day. This is obviously an intolerable situation." [9, p.1] Second, there is a significant danger of accidents, because the present system includes four grade crossings with attendant parking ramp car and pedestrian traffic. As Mr. Leean further notes, "[t]he on grade crossings are another major concern because of the over two million vehicles per year that cross at a direct right angle to the shuttle route. This is a significant accident potential and one that must be addressed in any long term planning."

As part of its long-range plans to deal with capacity and safety issues, the MAC proposes to build an enclosed Ground Transportation Center, located beneath the lower level roadway, which would provide access to rental car companies, parking ramps, and mass transit services including buses and limousines. Several major problems arise with this proposed Ground Transportation Center.
1. Because the shuttle route would be closed-in, the chosen transit mode needs to be quiet and non-polluting.

2. The tight turning radius of the airport-side terminus makes compliance with the Americans with Disabilities Act (requiring handicapped accessibility for all major facility and equipment upgrades) very problematic for buses.

3. Any transit mode would need to be able to accommodate more than 2,000 passengers per hour "... by slightly after the year 2000, and certainly by the year 2010." [9, p.2]

Given these problems, RPEVs represent no significant improvement over the existing shuttle system for two reasons:

1. Though RPEVs would provide a quieter and less polluting option (at a much higher capital cost) to the currently used diesel buses, they do not solve the capacity problem. "[T]he simple adding of additional buses does not solve capacity issues, and in fact, probably degrades capacity because one bus would only end up being in another's way." [9, p.1]

2. RPEVs offer no better solution to potential car and pedestrian accidents than diesel buses.

In a below grade shuttle system, as envisioned in the proposed Ground Transportation Center, RPEVs would not fit MAC needs well, because they do not solve a) the capacity and b) the tight turning radius problems.

For these reasons, as well as the fact that drivers constitute the biggest cost of operation in the current shuttle system, MAC planners are considering a below-grade, automated, two-track people mover system that could move up to 2,042 people per hour.

In sum, RPEVs does not offer the Minneapolis St. Paul International Airport an attractive alternative to solve the varied transit problems it faces.
VI CONCLUSION

Capital costs make the LRT transit system the costliest system to build, though it is difficult to feel confident about the actual numbers involved with all three transit modes. Capital costs ought to be taken seriously only insofar as they represent a certain order of magnitude. This is especially true about E-TRAN's RPEV since an RPEV system has not been built. Once an LRT system is built, however, it effectively competes on a revenue mile basis with ETBs and diesel buses and offers a city an effective way to move people around lessening congestion costs and reducing pollution levels in city core areas. An RPEV system, though with a higher capital cost than diesel buses and a very roughly comparable capital cost with ETBs offers a promising means of transportation, though one which requires full-scale testing to determine important cost information.

In general, cities would need high ridership to justify the high initial capital cost of an LRT system. A limited line where high ridership is readily apparent (and verified on existent bus lines) could justify LRT. Trolley buses, with their overhead wires offer a daunting aesthetic barrier as well as significant route inflexibility that make them an unattractive option, though use of dual mode bus would make the choice more appealing. RPEVs, similarly handicapped with high capital costs, do offer one significant advantage in that car-pooling vehicles equipped with a pantograph could share a high-occupancy-vehicle lane; with more automobiles, however, comes the risk of congestion and slower bus speeds. RPEVs could best be used in continuous loop operation where pollution concerns are significant.

In sum, the current automobile-centered transit policy is very costly and getting more so. More buses and fewer automobiles are necessary steps toward a more sustainable transit policy; electric vehicles are part of such a policy if the public wishes to pay the high capital costs they entail. This study concludes that RPEVs seem to be in the same general capital cost arena as ETBs. LRT systems are clearly the most expensive and should be looked at only after a sober and realistic appraisal of potential new ridership is undertaken. With respect to operating costs, LRT vehicles are more expensive according to a variety of efficiency measures except for costs per passenger mile. Electric transit has desirable environmental benefits over diesel buses and automobiles in congested areas, but it is questionable whether people are willing to pay more to have the quieter, cleaner, local environment electric transit offers.

This study's contention is that any reasonable transit policy ought to start with the lowest cost options first, which include encouraging people to purchase fewer and less-polluting
automobiles (using taxes), designing systems to move traffic more efficiently on highways, facilitating bicycle commuting, using more energy-efficient buses more effectively, and only then ought one to consider electric transit options. It seems reasonable that in Minneapolis-St. Paul, where pollution problems are not as serious in comparison with cities such as Los Angeles, transit solutions will focus more heavily on congestion reduction strategies than pollution reduction so that better car management, more effective diesel bus use, perhaps a short LRT spur (if ridership expectations warrant it), and RPEV loops connecting bus routes seem to suggest a reasonable strategy.
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COST COMPARISON STUDY

APPENDIX

Total Capital Costs for the Twin Cities (proj.) And Recently Constructed LRT Systems

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Mpls/St Paul</th>
<th>Portland</th>
<th>Sacramento</th>
<th>San Jose</th>
<th>Pittsburgh</th>
<th>Los Angeles</th>
</tr>
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<tbody>
<tr>
<td>Guideway Elements</td>
<td>141.00</td>
<td>106.60</td>
<td>47.90</td>
<td>56.10</td>
<td>124.00</td>
<td>135.10</td>
</tr>
<tr>
<td>Yards &amp; Shops</td>
<td>30.60</td>
<td>13.40</td>
<td>4.10</td>
<td>18.90</td>
<td>42.80</td>
<td>40.20</td>
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<tr>
<td>Systems</td>
<td>85.90</td>
<td>23.80</td>
<td>20.00</td>
<td>26.50</td>
<td>66.10</td>
<td>104.70</td>
</tr>
<tr>
<td>Stations</td>
<td>55.00</td>
<td>16.90</td>
<td>10.50</td>
<td>4.00</td>
<td>38.50</td>
<td>59.90</td>
</tr>
<tr>
<td>Vehicles</td>
<td>59.80</td>
<td>33.20</td>
<td>34.90</td>
<td>51.70</td>
<td>64.40</td>
<td>72.60</td>
</tr>
<tr>
<td>Special Conditions</td>
<td>6.50</td>
<td>12.50</td>
<td>7.50</td>
<td>11.30</td>
<td>150.70</td>
<td></td>
</tr>
<tr>
<td>Right of Way</td>
<td>19.20</td>
<td>17.00</td>
<td>17.90</td>
<td>49.40</td>
<td>24.80</td>
<td>54.60</td>
</tr>
<tr>
<td>Soft Costs</td>
<td>82.60</td>
<td>65.10</td>
<td>40.20</td>
<td>120.80</td>
<td>252.20</td>
<td>208.40</td>
</tr>
<tr>
<td>TOTAL</td>
<td>474.10</td>
<td>282.50</td>
<td>188.00</td>
<td>334.90</td>
<td>624.10</td>
<td>826.20</td>
</tr>
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</table>

Sources: Mpls-St.Paul data comes from the Central Corridor Summary Document and data about other systems comes from Table 2-13 of the September, 1992 "Characteristics of Urban Transportation Systems" published by the Federal Transit Administration, U.S. Department of Transportation