Operational Analysis of At-Grade Light Rail Transit

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At-grade operation of light rail transit (LRT) presents many analytical problems not normally encountered in traffic engineering analysis. In particular, the non-cyclical and directional nature of LRT arrivals renders traditional intersection and network analysis techniques inappropriate. In planning or designing an LRT system, the information often required by decision-makers includes delay to LRT due to street traffic, delay to street traffic due to LRT, length of queues when LRT affects traffic signals or at-grade crossings, short-term and long-term levels of congestion at at-grade crossings, and the impacts of combined events such as back-to-back rail vehicle arrivals. Computer-based tools have been developed to provide this information in both the planning and design stages of LRT system projects, including estimating average degree of saturation at a traffic signal during an hour of LRT operation, estimating cycle-by-cycle delays and queue length at a preempted fixed-time signal with LRT arrivals at preset headways, and estimating LRT delay in a fixed-time coordinated signal system with partial or no LRT priority. A new general purpose network simulator has been created that will realistically model light rail vehicles in a street environment with vehicle-actuated and coordinated traffic signals and other controls.

NORTH AMERICA IS EXPERIENCING a boom in light rail transit (LRT) after more than half a century of devotion to the automobile that saw the demise of all but a few LRT systems. More and more cities are turning to light rail as an economical alternative to their traffic-clogged freeways and urban streets. Urban development in many areas has reached the stage at

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593
which freeways will not be able to provide the capacity required in the future, particularly for commuting. LRT provides an alternative means of increasing the transportation system's capacity without the capital intensiveness and dislocation associated with new freeways or new heavy rail or metro lines.

A number of cities in North America are planning new or extended LRT systems that involve at-grade operations and the challenge of integrating LRT with street traffic. The operational analysis of both automobile traffic and light rail with at-grade operations is difficult at the best of times but is becoming more important as planners and engineers strive to develop the most efficient systems possible with the resources available. Major investment decisions such as grade separations and vehicle fleet size hinge on the quality of the analysis. This paper describes the analytical tools used by the authors for the planning and design of at-grade operations on six different LRT systems.

BACKGROUND

San Francisco led the way for modern light rail on the West Coast with the introduction of the 3.2-mi (5.1-km) Market Street transit subway for the San Francisco Municipal Railway (Muni) as part of the Bay Area Rapid Transit (BART) project. The new subway linked all five of Muni's surviving streetcar lines, which were rehabilitated and reequipped with 140 Boeing Vertol articulated standard light rail vehicles (LRVs). Two at-grade extensions to the system are being designed.

With the opening of the San Diego Trolley in 1981, San Diego became the first U.S. city since the early part of the century to open a new light rail system. Linking downtown San Diego with the Mexican border, it uses Siemens/Duewag U2 articulated vehicles. New lines are partially completed or planned as part of an ultimate regional light rail system of 113 mi (180 km).

Sacramento's Regional Transit District (RTD) opened an 18-mi (29-km) RT Metro in 1987 utilizing U2 cars on abandoned freeway segments, old and existing railroad rights-of-way, shared street alignments, and a transit mall. Currently operating on both single- and double-track segments, RTD plans full double tracking and future development in four corridors. This will extend the two existing lines and add two new lines radiating from downtown to the airport and major residential areas.

The Santa Clara County Transportation Agency (SCCTA) opened the first stage of the Guadalupe Corridor light rail line at the end of 1987, using Canadian UTDC articulated cars. The line, linking residential areas with downtown San Jose and the Silicon Valley industrial parks, will operate in a
The Los Angeles County Transportation Commission (LACTC) has two light rail lines under construction. One is a 21-mi (34-km) line from downtown Los Angeles to Long Beach, scheduled to open in 1989. The second line runs from Norwalk to El Segundo and will operate mostly in the median of the new Century Freeway. Sixty miles (96 km) of LRT line are expected to be in operation or under construction by the end of the century. Using Sumitomo articulated vehicles, the lines will operate in the full range of environments—subway, railroad right-of-way, freeway median, and on-street.

Work has recently resumed on the design of a 14-mi (22 km) LRT system in the Woodward Avenue corridor in Detroit, Michigan. Much of the system is planned to operate at-grade in median and side-running alignments. The project was delayed while all resources were focused on the completion of Detroit's downtown people mover.

These six projects have involved the authors in operations analyses at various stages of the LRT development process, such as corridor selection, alternatives analysis, environmental impact assessment, alignment selection, preliminary design, and final design. The analyses have been used for different purposes, including estimating LRT travel time and energy consumption, assessing impacts on automobile traffic and pedestrians, determining the need for grade separations, and selecting the best design alternative. The level of detail and confidence needed in each analysis varied depending on its purpose and the stage of the LRT development process. In all cases, the analyses focused on the interaction between road and rail vehicles at those points where automobiles are able to drive on or across the LRT tracks.

THE ANALYSIS CHALLENGE

At-grade LRT presents special challenges not found in traditional rail or road traffic operations analysis. This is due to several factors. The wide variety of geometry, traffic control devices, and operating conditions encountered within a single LRT project all require consistent analysis. The sporadic and random nature of the interaction between LRVs and road vehicles must be considered. And the interdependence of events occurring at adjacent grade crossings, or during consecutive LRV arrivals, also comes into play.

Variety of Conditions

The following are some of the different conditions encountered in these LRT projects:
• Single or double track;
• Headways varying from 2 min to 20 min;
• Tracks located in a separate right-of-way, at the side of the street, in the street median, or in a traffic lane;
• One-way or two-way streets;
• Freight trains on the same tracks or on adjacent tracks;
• Signalized or unsignalized intersections;
• At-grade crossings or grade-separated crossings;
• Crossings at midblock locations, beside intersections, within intersections, or at driveways;
• LRT tracks crossing straight across the roadway, turning within an intersection, turning midblock from the median to side-running or separate right-of-way, branching, or within a traffic lane (mixed flow);
• Crossings closer together than the maximum length LRV, or crossings of two legs of an intersection to form a triangle;
• Nearside and farside stations;
• Traffic signals that are fixed time or actuated, coordinated or uncoordinated, and preempted or not preempted; and
• Various degrees of LRT priority at traffic signals, ranging from no priority, through window stretching, to emergency-vehicle-style priority (1).

To maintain credibility and to allow accurate comparison of alternatives, the operations analysts were required to be consistent in the conduct of analyses from one situation to the next, and from one stage of the project to the next. Yet the situations at different crossings or in different alternative designs for a single crossing were often totally different, as indicated by the list of variations above. Similarly, the levels of detail needed at different stages of the project differed substantially. When different analysis tools or techniques were used for different situations or stages of the project, the results often appeared inconsistent. The credibility of the analysts was not helped by the need to make different simplifying assumptions for different analyses.

Sporadic and Random Arrivals

LRVs do not arrive at fixed headways and do not always arrive separately. Even if the schedule calls for uniform headways, schedule adherence is never perfect, especially in an at-grade LRT system. In double-track sections, the LRVs traveling in opposite directions may arrive at the crossing simultaneously, one immediately after the other, or at various separation times. If they happen to arrive at a crossing simultaneously, the impact on automobile traffic is much less than if they arrive at different times. If one LRV arrives
immediately after another (in opposite directions), the overall impact may be much greater than for separate arrivals. It was found necessary to consider all possible arrival patterns and assign probabilities of occurrence of each pattern.

**Interdependence of Events**

LRV arrivals at crossings separated by time or distance were often found to influence each other, rather than being independent, as assumed by most analysis techniques. For example, an LRV that arrives at a traffic signal shortly after another LRV in the opposite direction may be subjected to additional delay if the LRV priority measure in the signal controller is excluded from operation in consecutive signal cycles. Such interdependency can invalidate the assumption of random arrivals normally used in assigning probabilities to alternative arrival scenarios. Traffic signal coordination further complicates attempts to estimate LRV arrival patterns and their probabilities of occurrence.

**ANALYSIS TECHNIQUES AND APPLICATIONS**

Several different analysis procedures and associated computer programs have been developed for use on LRT projects.

**Basic Capacity Analysis**

The first step in analyzing alternative at-grade arrangements, whether at intersections or at midblock crossings, is to perform a basic traffic capacity analysis. Although this is often limited because of its reliance on average arrival and departure rates, fixed cycle lengths, and predictable headways, it does provide a primary screening process that eliminates alternatives with obviously insufficient capacity.

For this purpose, computer programs were developed that follow the 1985 Highway Capacity Manual (HCM) (2) operations analysis procedures to determine volume/capacity ratio, average delay, and level of service at an intersection or midblock crossing at which signal cycle length and LRV headways are assumed fixed and constant. In this software the HCM methods are extended to include percentage of vehicles stopped and probabilistic measures of queue length (3).

Midblock at-grade crossings were treated as a traffic signal with a cycle length equal to the average LRV or train headway. At crossings where LRVs were subject to traffic signal control, the impacts of LRT were assumed to be
represented by the average signal timing, taking into account the appearance of extra LRV phases or LRV priority in some cycles. On the basis of these assumptions, the computer programs were used to analyze the capacity of a crossing to cater to automobile traffic and LRVs. While this identified crossings that do not have sufficient capacity to serve demands over a period of time (such as the peak hour), it did not adequately analyze the effects of variable headways and back-to-back arrivals. It provided a reasonable approximation for low-frequency, single-track crossings, such as found in Sacramento, where LRVs operate on 15- to 20-min headways. It is clear from Figure 1 that the typical intersection with LRT phasing presents complexities that cannot be handled by this approach in high-frequency situations.

![Figure 1 Typical phasing for on-street LRT operation.](image)

**Variable LRV Headway**

The next level of analysis sophistication was developed to account explicitly for the fact that LRVs do not arrive at fixed headways and do not always arrive separately. Another computer program was developed for these situations. A time-series pattern of LRV arrivals was superimposed on the traffic signal cycle, determining periods during which each automobile movement may or may not flow. Where freight trains used the same right-of-way, the train arrivals were also added into the event pattern. The queue growth and decay patterns were then modeled to derive delays and queue lengths.

To investigate the effect of variations in headways, several runs were made with different headway assumptions. The results were used to estimate the range of impacts, the worst case, and the average condition. This procedure was found to be useful in investigating both levels of service and the potential for queue interference at adjacent intersections.

As an example, this software was used recently in analyzing alternatives for a Muni Metro extension in San Francisco. The Embarcadero subway
station has a double-track, stub-end terminal with scissors crossover and is the terminus for all five Muni LRT lines. Although early plans called for an underground loop, current planning calls for a surface turnback facility with a new station along the waterfront Embarcadero. Figure 2 illustrates the 90th percentile queue lengths expected on each approach of LRT at-grade crossings for one of the alternatives investigated, indicating the extent of disruption that queueing will have on adjacent intersections.

Another application of this technique to an unusual combination of mid-block crossings adjacent to a preempted signal is illustrated in Figure 3. The worst-case pattern of LRVs at the crossing was shown to cause the tracks to be blocked by queues that could not always be cleared without oversaturating the cross street.

**LRV Travel Times**

In many applications, traffic conditions dictate that light rail cannot be given full priority or preemption at all grade crossings or intersections. Various schemes giving LRT partial priority or even no special priority introduce delay to LRVs that needs to be quantified in order to compare alternatives and refine travel time and fleet size estimates. Statistical measures of travel time through one or more fixed cycle-length signalized intersections were derived using another computer program. Predetermined LRV windows were coded to model full priority, partial priority, or no priority for light rail at a series of signalized crossings. Estimates of the mean and standard deviation were calculated for travel time (and hence delay) on each link and overall. Table 1 illustrates the type of information that can be derived from this model, which is particularly useful at the planning level as input to economic evaluation and supplementary to basic capacity analysis. This approach gave more accurate results than the available heavy rail simulation models, which typically introduce intersection delay as an exogenous variable rather than calculating it.

**Comprehensive Operational Analysis**

Each program just described offers an improvement over simple intersection capacity analysis and continues to be appropriate when the underlying assumptions are valid and the approximations are adequate. However, none offers integrated analysis of LRVs and automobile traffic with the flexibility to model all situations accurately, including vehicle-actuated signals (isolated and coordinated) and variable LRV headways on single or double track. For this purpose, the authors developed a microscopic simulator called ROAD-TEST (4).
FIGURE 2  Expected 90th percentile queue lengths at signalized intersections with full LRT priority.
FIGURE 3 Queue behavior at preemtpted signal adjacent to gated crossing.

TABLE 1 LRT DELAY WITH PARTIAL PRIORITY WITH AT-GRADE LRT IN EMBARCADERO MEDIAN IN SAN FRANCISCO

<table>
<thead>
<tr>
<th></th>
<th>Northbound</th>
<th>Southbound</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percent stopped</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bryant</td>
<td>58</td>
<td>59</td>
</tr>
<tr>
<td>Folsom</td>
<td>24</td>
<td>28</td>
</tr>
<tr>
<td>Average delay (sec/train)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bryant</td>
<td>14</td>
<td>14</td>
</tr>
<tr>
<td>Folsom</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Total average delay (sec/train)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>17</td>
<td>17</td>
</tr>
<tr>
<td>Range (sec)</td>
<td>0-45</td>
<td>0-46</td>
</tr>
</tbody>
</table>
ROADTEST is a microscopic rail and road traffic simulation model. It simulates the movement of all the individual vehicles in a road and rail network of any size and any complexity. It simulates both automobiles and LRVs, and can also simulate freight trains, buses, pedestrians, and other vehicle types if needed. Both traffic signals and train control signals are modeled in detail, including vehicle detectors and track circuits.

Various output reports at different levels of detail show statistics for measurements such as travel time, delay, stops, queue lengths, time and duration of events, etc. These statistics can be disaggregated in various ways, including by network segment, vehicle type, or route. As part of its output, ROADTEST also produces an animated graphical display of the network and vehicles in each time slice (e.g., one-fifth of a second). The user has complete control of the display via zoom, pan, slow motion, freeze, and similar commands. One of these movie frames is shown in Figure 4.

The animated display has proven to be invaluable in checking the performance of the model and simplifying the calibration process. It also provides observers with visual confirmation that this is a realistic and accurate model, thus removing one of the greatest barriers to acceptance of traditional computer model outputs. It shows LRT and traffic operations at a greater level of detail and understanding than is possible with numerical output alone.

ROADTEST directly addresses all of the problems and limitations associated with the other analysis techniques discussed above. It can model any situation encountered, with both rail and road vehicles, and any signal system or network. Thus it provides a single consistent source of accurate operations analysis data. It can also be used for failure management planning, schedule development, and supervisor training.

Table 2 shows output from a ROADTEST simulation of one of the critical intersections involved in the San Francisco Muni Metro extension project. These individual time period results were found useful in identifying short periods of oversaturation within a peak period that otherwise had an acceptable average performance.

SUMMARY AND CONCLUSIONS

The authors' analysis of at-grade LRT operations on six different LRT systems presented many challenging problems. At-grade light rail systems require an extraordinary analysis effort due to:

- The wide variety of geometry, control devices, and operating conditions encountered within a single LRT project, all requiring consistent analysis;
- The sporadic and random nature of the interaction between LRVs and road vehicles; and
FIGURE 4 Computer-assisted-drafting plot of ROADTEST animated screen.
## TABLE 2 ROADTEST TRAVEL REPORT

**SAN FRANCISCO MUNI METRO EXTENSION**
**EMBARCADERO AT FOLSON**

**Included Vehicle Types:** compactcar midsizecar largecar

**Entry Locations:** EB_IN_5_IN EB_IN_6_IN EB_IN_7_IN

**Exit Locations:** NB_OUT_8_OUT NB_OUT_9_OUT SB_OUT_10_OUT SB_OUT_11_OUT

<table>
<thead>
<tr>
<th>Time Period (Hr:Min)</th>
<th>No. of Vehs</th>
<th>Distance Travelled (Miles)</th>
<th>Travel Time (Mins:Secs)</th>
<th>Ave Speed (mph)</th>
<th>% Vehs Stop</th>
<th>Number of Stops</th>
<th>Stopped Delay (Mins:Secs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>00:00 to 00:05</td>
<td>32</td>
<td>510.8</td>
<td>00:25:45 00:48 00:23:01 01:19</td>
<td>16.0</td>
<td>84%</td>
<td>324</td>
<td>0.8 0.0 1.0 0.4</td>
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<tr>
<td>00:05 to 00:10</td>
<td>45</td>
<td>938.4</td>
<td>00:27:44 00:36 00:23:01 01:01</td>
<td>20.9</td>
<td>76%</td>
<td>408</td>
<td>0.8 0.0 1.0 0.4</td>
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<tr>
<td>00:10 to 00:15</td>
<td>44</td>
<td>899.6</td>
<td>00:27:39 00:37 00:22:00 00:57</td>
<td>20.4</td>
<td>68%</td>
<td>360</td>
<td>0.7 0.0 1.0 0.5</td>
</tr>
<tr>
<td>00:15 to 00:20</td>
<td>40</td>
<td>775.0</td>
<td>00:26:36 00:39 00:21:00 00:01</td>
<td>19.4</td>
<td>73%</td>
<td>348</td>
<td>0.7 0.0 1.0 0.5</td>
</tr>
<tr>
<td>00:20 to 00:25</td>
<td>59</td>
<td>1104.0</td>
<td>00:44:08 00:44 00:22:01 00:31</td>
<td>17.2</td>
<td>83%</td>
<td>432</td>
<td>0.8 0.0 1.0 0.4</td>
</tr>
<tr>
<td>00:25 to 00:30</td>
<td>45</td>
<td>737.5</td>
<td>00:35:16 00:47 00:23:00 00:29</td>
<td>16.4</td>
<td>78%</td>
<td>420</td>
<td>0.8 0.0 1.0 0.4</td>
</tr>
<tr>
<td>00:30 to 00:35</td>
<td>52</td>
<td>1130.9</td>
<td>00:30:42 00:46 00:20:00 00:56</td>
<td>21.7</td>
<td>69%</td>
<td>408</td>
<td>0.8 0.0 1.0 0.4</td>
</tr>
<tr>
<td>00:35 to 00:40</td>
<td>37</td>
<td>765.2</td>
<td>00:22:59 00:37 00:22:00 00:54</td>
<td>20.7</td>
<td>68%</td>
<td>360</td>
<td>0.7 0.0 1.0 0.5</td>
</tr>
<tr>
<td>00:40 to 00:45</td>
<td>54</td>
<td>1192.7</td>
<td>00:31:26 00:34 00:21:00 00:56</td>
<td>22.1</td>
<td>56%</td>
<td>348</td>
<td>0.7 0.0 1.0 0.5</td>
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<tr>
<td>00:45 to 00:50</td>
<td>50</td>
<td>1080.3</td>
<td>00:29:47 00:35 00:21:00 00:55</td>
<td>21.5</td>
<td>70%</td>
<td>420</td>
<td>0.7 0.0 1.0 0.5</td>
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<tr>
<td>00:50 to 00:55</td>
<td>48</td>
<td>1014.2</td>
<td>00:29:10 00:36 00:24:00 00:53</td>
<td>21.1</td>
<td>70%</td>
<td>432</td>
<td>0.8 0.0 1.0 0.4</td>
</tr>
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<td>00:55 to 01:00</td>
<td>75</td>
<td>1340.9</td>
<td>00:53:54 00:43 00:20:00 00:57</td>
<td>17.9</td>
<td>87%</td>
<td>780</td>
<td>0.9 0.0 1.0 0.3</td>
</tr>
</tbody>
</table>

**ONE HOUR SUMMARY**

<table>
<thead>
<tr>
<th>Time Period (Hr:Min)</th>
<th>No. of Vehs</th>
<th>Distance Travelled (Miles)</th>
<th>Travel Time (Mins:Secs)</th>
<th>Ave Speed (mph)</th>
<th>% Vehs Stop</th>
<th>Number of Stops</th>
<th>Stopped Delay (Mins:Secs)</th>
</tr>
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<tbody>
<tr>
<td>00:00 to 01:00</td>
<td>714</td>
<td>13096.7</td>
<td>08:20:25 00:42 00:20:01:34</td>
<td>18.3</td>
<td>76%</td>
<td>546</td>
<td>0.8 0.0 2.0 0.4</td>
</tr>
</tbody>
</table>

**TOTAL**

<table>
<thead>
<tr>
<th>Ave</th>
<th>Min</th>
<th>Max</th>
</tr>
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<tbody>
<tr>
<td>Ave</td>
<td>Min</td>
<td>Max</td>
</tr>
<tr>
<td>Ave</td>
<td>Min</td>
<td>Max</td>
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</table>

<table>
<thead>
<tr>
<th>Ave</th>
<th>Min</th>
<th>Max</th>
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</table>
• The interdependence of events occurring at adjacent grade crossings or during consecutive LRV arrivals.

A range of analytical tools has been developed that permits study of LRT and related automobile operations to varying levels of detail with concomitant levels of accuracy. The most sophisticated of these is the ROADTEST simulator, which integrates LRVs and automobile traffic into a single task using a general purpose network simulation procedure.

REFERENCES