OPTIMIZING TRAFFIC NETWORK SIGNALS AROUND RAILROAD CROSSINGS

By
Li Zhang

Dissertation submitted to the faculty of the Virginia Polytechnic Institute and State University in partial fulfillment of the requirements for the degree of Doctor of Philosophy
In
Civil and Environment Engineering

Antoine G. Hobeika, Chairman
Raj Ghaman
Wei H. Lin
Antonio A. Trani
Brian D. Woerner

12 May 2000
Blacksburg, Virginia

Keywords: Traffic Signal Optimization, Grade Crossing Safety, Neural Network, Intelligent Agent
OPTIMIZING TRAFFIC NETWORK SIGNALS AROUND RAILROAD CROSSINGS

Li Zhang

Abstract

The dissertation proposed an approach, named “Signal Optimization Under Rail Crossing Safety Constraints” (SOURCAO), to the traffic signal control near a highway rail grade crossing (HRGC). SOURCAO targets two objectives: HRGC safety improvement (a high priority national transportation goal) and highway traffic delay reduction (a common desire for virtually all of us). Communication and data availability from ITS and the next generation train control are assumed available in SOURCAO.

The first step in SOURCAO is to intelligently choose a proper preemption phase sequence to promote HRGC safety. An inference engine is designed in place of traditional traffic signal preemption calls to prevent the queue from backing onto HRGC. The potential hazard is dynamically examined as to whether any queuing vehicle stalls on railroad tracks. The inference engine chooses the appropriate phase sequence to eliminate the hazardous situation.

The second step in SOURCAO is to find the optimized phase length. The optimization process uses the network traffic delay (close to the control delay) at the intersections within HRGC vicinities as an objective function. The delay function is approximated and represented by multilayer perceptron neural network (off-line). After the function was trained and obtained, an optimization algorithm named Successive Quadratic Programming (SQP) searches the length of phases (on-line) by minimizing the delay function. The inference engine and proposed delay model in optimization take the on-line surveillance detector data and HRGC closure information as input.

By integrating artificial intelligence and optimization technologies, the independent simulation evaluation of SOURCAO by TSIS/CORSIM demonstrated that the objectives are reached. The average network delay for 20 runs of simulation evaluation is reduced over eight percent by a t-test while the safety of HRGC is promoted. The sensitivity tests demonstrate that SOURCAO works efficiently under light and heavy traffic conditions, as well as a wide range of HRGC closure times.
GRANT INFORMATION

This research is partially supported by the Federal Railroad Administration, the US Department of Transportation through Eisenhower Grants for Research Fellowship (Grant No. DDEGRF-97-X-00420). In addition, this research is partially sponsored by the Federal Highway Administration, the US Department of Transportation (Prime Contract No. DTFH61-97-C-0055) through sub-contract with ITT Industries, Systems Division (Formerly, Kaman Sciences, Sub-contract No. C-98-01/PO 1900015).
ACKNOWLEDGMENTS

The author would like to thank his major advisor Dr. Antoine G. Hobeika for his guidance and support. He is grateful to his advisory committee, Mr. Raj Ghaman, Dr. Wei H. Lin, Dr. Antonio A. Trani, Dr. Brian D. Woerner and Dr. Donald Drew (retired from committee), for their helpful suggestions and encouragement. He sincerely appreciates Dr. Trani’s critical review of his entire dissertation.

His dissertation research is partially sponsored by Traffic Research Laboratory, Tuner Fairbank Highway Research Center. The author would like to thank the Advanced Traffic Management Team, the Federal Highway Administration, especially, Mr. Raj Ghaman for his knowledge of traffic signal control, Ms. Curtis Deborah for her kindness and her help on RT-TRACKS and Dr. Henry Lieu’s help on TSIS/CORSIM.

The author would like to express his gratitude to his supervisors at ITT Industries, Mr. Larry Owens and Mr. Juan Morales, for their support and encouragement; his colleagues, Dr. Shiow-Min Lin and Ms. Meenashky Vasudevan for their encouragement and various helps.

During his dissertation research at the Federal Railroad Administration, his research activities were largely supported by the Office of Research and Development. Special thanks are given to his technical advisor Dr. Thomas Tsai for his encouragement and guidance. In addition, Mr. Steve R. Ditmeyer provided his thoughtful insights about the Highway Rail Intersection under the umbrella of the National Architecture of ITS. Mr. Robert McCown offered his extensive knowledge about the Next Generation of Train Control. Mr. Jim Smailes gave the New York Long Island grade crossing projects. Mr. Steve Jennings (consultant) presented his personal affection and various grade crossing improvement projects around the States. Beyond that, the author would like to express his appreciation to Mr. John Hitz of Vople National Transportation Systems Center for his support. They made the “Improvement of Grade Crossing Safety” as one of the two dissertation research goals.

The author also benefits the dissertation research from his education, teaching and research experiences in China. Special thanks are sent to Professor Yuicai Deng at Southwest Jiaotong (Means Communication and Transportation) University and Professor Qichang Zhen at Shanghai Tiedao (Railroad) University for their remote encouragement.

Finally, he is deeply indebted his dear wife—Nie, Wei—for her love and support during the writing of this dissertation. He thanks his grandmother, who brought him up, and his parents who encouraged him to finish his dissertation. He affectionately dedicates this dissertation to them.
TABLE OF CONTENTS

CHAPTER 1 INTRODUCTION 1

1.1 Background 1

1.2 Objectives 2

1.3 Solution 3

1.4 Organization of the Dissertation 4

CHAPTER 2 LITERATURE REVIEW 5

2.1 Introduction 5

2.2 Highway Rail Grade Crossing Safety 5

2.3 Highway Traffic Control near Highway Rail Grade Crossing 18

2.4 Traffic Signal Optimal Control with Priority Vehicles 31

2.5 The Application of Artificial Intelligence to Traffic Control 39

2.6 Traffic Simulation 44

2.7 Summary 46

CHAPTER 3 SYSTEM OVERVIEW 47

3.1 Introduction 47

3.2 Objectives 47

3.3 Methodologies 53

3.4 System Architecture 55

3.5 System Function Requirements 67
<table>
<thead>
<tr>
<th>CHAPTER 4 OBJECTIVE FUNCTIONS</th>
<th>69</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.1 Introduction</td>
<td>69</td>
</tr>
<tr>
<td>4.2 Safety Surveillance</td>
<td>69</td>
</tr>
<tr>
<td>4.3 Traffic Delay Surveillance</td>
<td>72</td>
</tr>
<tr>
<td>4.4 Delay Model Formulation</td>
<td>74</td>
</tr>
<tr>
<td>4.5 Neural Network Delay Forecasting</td>
<td>80</td>
</tr>
<tr>
<td>4.6 Back-Propagation Training</td>
<td>93</td>
</tr>
<tr>
<td>4.7 Multilayer Perceptrons Implementation</td>
<td>96</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CHAPTER 5 METHODOLOGIES</th>
<th>101</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.1 Introduction</td>
<td>101</td>
</tr>
<tr>
<td>5.2 The Intelligent Agent and Grade Crossing Safety</td>
<td>101</td>
</tr>
<tr>
<td>5.3 Phase Length Optimization</td>
<td>108</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CHAPTER 6 VALIDATION AND EVALUATION</th>
<th>116</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.1 Introduction</td>
<td>116</td>
</tr>
<tr>
<td>6.2 The Verification and the Validation of Models</td>
<td>116</td>
</tr>
<tr>
<td>6.3 Evaluation Environment</td>
<td>127</td>
</tr>
<tr>
<td>6.4 Evaluation Results</td>
<td>139</td>
</tr>
<tr>
<td>6.5 Case Study Analysis</td>
<td>141</td>
</tr>
<tr>
<td>6.6 Sensitivity Analysis</td>
<td>145</td>
</tr>
</tbody>
</table>
LIST OF FIGURES

Figure 2-1 Train Speed and Accident Severity .............................................................. 10
Figure 2-2 High Speed Corridors .......................................................... 13
Figure 2-3 PTC Architecture .......................................................... 16
Figure 2-4 TPC Logic .......................................................... 26
Figure 2-5 NAITS Physical Architecture for HRGC ............................................. 27
Figure 2-6 NAITS Logical Architecture for HRGC ........................................ 28
Figure 2-7 The SPPORT Optimizer .......................................................... 35
Figure 2-8 PRIMAVERA Public Transportation System Architecture .................. 38
Figure 3-1 Data Flow at Interface between CORSIM and SOURCAO ..................... 57
Figure 3-2 SOURCAO Program Flow by the Class and the Function .................. 61
Figure 3-3 SOURCAO Program Flow .......................................................... 62
Figure 3-4 Inference Engine Data Flow .......................................................... 64
Figure 3-5 Delay Forecast Neural Network Training ........................................ 65
Figure 3-6 The Optimization Interface .......................................................... 67
Figure 4-1 Layout of Link Surveillance Detectors ................................................. 70
Figure 4-2 Two and Three Layer MLP Training Speed ......................................... 99
Figure 4-3 Declining Error with the Time in Back-Propagation 3 ........................ 100
Figure 5-1 A Reflex Agent with Internal State ...................................................... 103
Figure 5-2 A Traffic Control Reflex Agent ......................................................... 103
Figure 5-3 Traffic Signal Stages and Grade Crossing Closure ................................ 105
Figure 5-4 A CORSIM Signal Control Code (FHWA, 1999) ................................. 107
Figure 6-1 CORSIM Queue Delays and SOURCAO Delays ............................... 118
Figure 6-2 The Surveillance Layout for Node 42 and Node 43 ............................. 121
Figure 6-3 Preemption before the Arrival of a Train ........................................... 124
Figure 6-4 Queues before an HRGC ......................................................... 125
Figure 6-5 The Case Study Area map .......................................................... 128
Figure 6-6 Case Study Link-Node Diagrams ..................................................... 129
Figure 6-7 The Phase Timing Plan for Node 12 ....................................................... 132
Figure 6-8 The Phase Timing Plan for Node 42 ................................................................. 133
Figure 6-9 Grade Crossing Closure Time Distributions .................................................. 137
Figure 6-10 The Surveillance Layouts for Node 12 ........................................................... 138
Figure 6-11 Grade Crossing Close Time and Control Delays ........................................ 146
Figure 6-12 Traffic Volume and Control Delays ............................................................... 147
LIST OF TABLES

Table 2-1 Identified Research Needs by Priority.......................................................... 7
Table 2-2 Summary of Research Needs........................................................................ 7
Table 2-3 The Outcomes of Decision at HRGC ......................................................... 11
Table 2-4 Benefits of Applying Existing Warning Systems to all Crossings............... 14
Table 2-5 Grade Crossing Signal/Control Requirements from the FRA’s Action Plan ... 15
Table 2-6 A Summary on PTC Projects (Gallamore 1998)......................................... 16
Table 2-7 The Market Packages and Equipment Packages ....................................... 29
Table 3-1 Selected Classes and Member Functions .................................................... 59
Table 3-2 Grade Crossing States.................................................................................. 64
Table 4-1 Types of Surveillance in SOURCAO........................................................... 70
Table 4-2 Neural Network Training Input Nodes....................................................... 97
Table 6-1 MLP Errors................................................................................................. 119
Table 6-2 (Skip) Rules for Choosing a Phase............................................................. 122
Table 6-3 CORSIM Links and Corresponding Streets .............................................. 129
Table 6-4 Traffic Characteristics in Case Study.......................................................... 130
Table 6-5 Volumes on Entry Nodes............................................................................ 131
Table 6-6 Grade Crossing Average Closure Time in Cases ...................................... 136
Table 6-7 Simulation Results in 20 Runs .................................................................. 140
Table 6-8 Paired Control Delay Data Analysis......................................................... 141
Table 6-9 Grade Crossing Queue Time when the Gate is Closed............................... 142
Table 6-10 Optimized Phase Length Distributions.................................................... 144
Table 6-11 SOURCAO and HCM Phase Allocated Time........................................... 145
Table 6-12 CPU Execution Time Distributions for SQP Algorithm......................... 145
CHAPTER 1 INTRODUCTION

1.1 Background

Promoting highway rail grade crossing (HRGC) safety is one of the nation's priority transportation goals. However, accidents reveal that further research needs to be done on HRGC. During the past five years, there were 2358 fatalities at HRGCs across the States, which results in property damage of about 140 million dollars (BTS 2000).

HRGC safety is approached by both railroad and highway authorities. On the railroad side, the most common safety measures aim at preventing highway vehicles from entering the right of way within a grade crossing to conflict with trains. For example, traffic signal control and active warning devices (including gates) installed at grade crossing are considered the highest form of protection at HRGC, short of grade separation (ITE 1997).

On the highway side, in addition to the safety concerns at grade crossing, the congestion and the traffic delays are of interest. Closure of HRGC to yield railroad operations aggregates the highway vehicle delays. In a congested area, such a waiting queue would extend to nearby highway intersections, and further worsen the highway traffic situation. It is quite common that the highway intersection queue would spill back onto the railroad tracks as well.

If the latter occasion is likely to happen, the vehicles on the rail tracks threaten the safety of a grade crossing. Therefore, highway traffic signals are usually interconnected to the railroad track circuits, which preempt the signals to respond arrival/departure of a train. The preemption is assumed to clear the vehicles on the tracks before the arrival of the train. Although the preemption provides the extra safety protections to grade crossing, it could agonize the highway drivers in a congested traffic network because the preemption interrupts the normal highway traffic operations.
The literature review in CHAPTER 2 reveals numerous researches in traffic signal optimization for public transit preemption. However, none of traffic signal optimization algorithms has been found to be incorporated with the railroad preemption operations. Moreover, although it is uncovered that engineers have been advocated to pay attention to the preemption design elements (interconnection distance and when to preempt), the preemption practices are controversial. Therefore, one motivation behind this research is trying to bridge the gap between highway traffic signal optimization and railroad operations, or equivalently, trying to bring the railroad preemption and safety into highway traffic signal optimization.

Although it is realized, that traffic optimization with HRGC safety consideration needs more data and communication links than the most current systems could provide. The development of the high-speed train (HST) could provide needed data. Besides, Intelligent Transportation Systems (ITS), designed to improve the efficiency of the national transportation system, could make it possible to better coordinate the highway traffic optimization with the railroad operations as well.

1.2 Objectives

Before the dissertation goes further, some naming conventions are explored. First of all, Highway Rail Grade Crossing (HRGC) is adapted as the uniform term in this dissertation to replace Grade Crossing, Highway-Rail Crossing, Rail-Highway Grade Crossing, Roadway-Rail Intersections, Railroad-Highway Grade Crossing and Highway Rail Intersection. Next, the term "traffic control" connotes "highway/street traffic control" near an HRGC and does not include the grade crossing access control, unless it is specified. The railroad traffic signal control is not an object in this dissertation. Finally, the proposed system is named as “Signal Optimization Under Rail Crossing sAfety cOnstraints” and is abbreviated as SOURCAO.
In summary, grade crossing is a junction of the railroad and the highway judiciaries; therefore, both the railroad and the highway users’ concerns are addressed, and two objectives are formed. On the railroad side, the safety of a grade crossing is of the largest concern. The first objective of the proposed system is to promote the safety of grade crossing by preventing the highway traffic queue from backing onto the tracks. On the highway side, in addition to improving the safety at a grade crossing, the second objective is to minimize the traffic delay incorporated with preemption and railroad operations.

1.3 Solution

The author tries to integrate state-of-the-art technologies (intelligent agents, neural networks, optimization and objective-oriented modeling) to achieve the targeted objectives. The solution is divided into two steps, corresponding to the two objectives stated above.

The first step is to intelligently choose a proper preemption phase sequence to promote grade crossing safety. In the proposed system, an inference engine is designed to prevent the queue from backing onto a grade crossing. The inference engine is in place of traditional traffic signal preemption calls to take the on-line surveillance detector data and grade crossing closure information as input. The potential hazard is dynamically examined as to whether any queuing vehicle stalls on railroad tracks. The inference engine could eliminate the hazardous situation.

The second step is to find the optimized phase length. The optimization process uses the traffic network delay (close to the control delay) at the intersections within grade crossing vicinities as an objective function. The delay calibration is based on the proposed model in this research, and the model takes surveillance detector data as input. The optimization is implemented through two steps. In the first step, the delay function is approximated and represented by a multilayer perceptron (MLP) neural network (off-line training). After the function is trained and obtained, an optimization algorithm named
Successive Quadratic Programming (SQP) searches the optimized length of phases so that total delays in the network can be minimized (on-line).

The proposed system is validated and evaluated through a TSIS/CORSIM simulated traffic environment. The validation and the evaluation of the proposed system examine the correctness and effectiveness of the proposed system through a case study.

1.4 Organization of the Dissertation

The next chapter (CHAPTER 2) presents the literature review. CHAPTER 3 illustrates the overview of the entire dissertation; in CHAPTER 3, after the goals of the research are introduced, the methodologies applicable to the research follow. Moreover, the interface between the proposed system and the evaluation software (TSIS/CORSIM) is emphasized and the sub-systems are introduced. CHAPTER 4 formulates the objective functions of the proposed system in this research. The chapter introduces the surveillance for both safety and delay first. Next, a delay model is proposed to incorporate with delay surveillance. Finally, a multilayer perceptron network is applied to forecast the delay. CHAPTER 5 presents the methodologies towards the solution of the objective functions. The details of intelligent agent design and SQP algorithm are addressed. CHAPTER 1 describes the validation and the evaluation of the proposed systems. The validation includes the proposed delay model, the neural network forecast, the traffic control intelligent agent and the SQP algorithm. The evaluation of the proposed system is based on a case study. Finally, CHAPTER 1 presents conclusion and recommendations.