Highway 404 HOV Tunnel Advance Warning System
(Innovative Solution to At Significantly Reduced Capital Costs)

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ABSTRACT

During the design stage, the Ministry identified safety concerns about the forthcoming Highway 404 High-Occupancy Vehicle (HOV) tunnel being introduced. Based on the design, motorists entering the tunnel at design speed will have adequate line-of-sight for lane blockages or queues. However, motorists violating the speed restrictions pose a heightened risk in terms of potential collisions. Consideration was given to alternative tunnel geometries that would inherently improve safety however, these alternatives were far too costly with little return in improved safety.

An Advance Warning System (AWS) was proposed. The AWS is an automated system designed to improve tunnel safety, reduce the potential for both primary and secondary collisions, and to reduce incident response times. The Advanced Warning System was successfully commissioned with Ontario's official HOV lane opening on December 13, 2005 and is fully meeting and exceeding the original goals for improved motorist safety and incident management. The warning messages provided on the signs has exceeded the degree of safety of a multi-million dollar geometric realignment, however at a fraction of the cost. This system is the first of its kind in North America and will set the new standard for exceptionally safe and efficient freeways in Ontario.

BACKGROUND

Introduction

As part of the Ministry of Transportation's Highway 404 widening, a single 11.2 km High Occupancy Vehicle (HOV) lane, or carpool lane, and 90m bypass tunnel were constructed Southbound from Van Horne Avenue to Highway 401. A location map is shown in **Figure 1**. This new tunnel, shown in **Figure 2**, links HOV traffic to the Highway 401 Westbound Collector lanes and is built to encourage Toronto's daily commuters to carpool and use buses. The lane usage is strictly enforced to ensure that only HOV vehicles (e.g., cars with more than two occupants, buses, etc) use the lane. The HOV tunnel is intended to provide fast, reliable travel for HOV users, especially during peak travel periods when other lanes can be congested.

In order to enhance the safety of motorists approaching the tunnel, an Advance Warning System (AWS) was developed. It provides advance notice of anticipated ramp queues building from reoccurring traffic congestion on Highway 401, as well as reduces the Ministry's incident response times. The AWS was commissioned with the HOV lane opening on December 13, 2005.

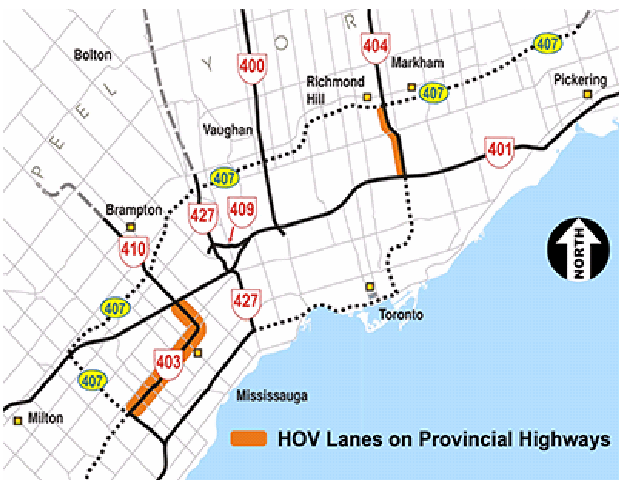

Figure 1 – Location Map

Figure 2 – Highway 404 HOV Tunnel

Problem Definition

During the early stages of design, concerns were raised about the safety of the forthcoming Highway 404 HOV tunnel. Due to physical space and cost constraints, the Highway 404 HOV freeway ramp tunnel was designed with an interpolated design speed of 55 km/hr and a wider right shoulder to provide a stopping sight distance based on a 60 km/hr design speed. While the tunnel was built to current Ministry standards, and the advisory speed limit of 40 km/h provides ample safety factor, speeding motorists pose an increased risk.

Consideration was given to alternative tunnel geometries that would inherently improve safety; however, these alternatives were far too costly with little return in improved safety.

As an alternative, an Intelligent Transportation Systems (ITS) solution was investigated to improve safety and provide a means for the Ministry's COMPASS Operations to manage incidents within the tunnel. The key objectives of the system design are to:

- Provide a means for automated real-time advance notice to motorists entering the tunnel of queues or lane blockages that may be beyond their sight;
- Provide a means for COMPASS Operations to manage incidents within the tunnel if and when they should occur;
- Provide a means for automatic dissemination of information on overall system events (i.e. detection of queues, incidents, and equipment malfunctions) preferably via automatic email; and;
- Provide a means for remote Ministry LAN access to monitor and manually override when required (i.e. freeway maintenance activities, etc).

The Ministry's COMPASS Operations currently manages sections of freeways throughout Ontario using cameras, variable message signs, and traffic sensors.

Solution

The mandate to provide incident management in the tunnel prompted the decision to add cameras; however, the Ministry project team took it one step further and employed enhanced technology that addresses all of the initially identified needs. An automated Advance Warning System was proposed to minimize rear-end collisions and provide advance notice of incidents and anticipated ramp queues building from the congested Highway 401. The technological solution provided a means to achieve a heightened degree of safety at a fraction of the cost of alternative tunnel geometrics. An aerial view of the completed project is shown in **Figure 3**.

This AWS utilizes similar field-proven strategies deployed at Ontario's award-winning Queue Warning Systems commissioned in February 2003 on the QEW and Highway 405 in Niagara Region. These systems provide automated real-time advanced warning of queues approaching two of Canada's busiest international border crossings.

The Highway 404 AWS is the first system in North America to successfully integrate two technologies—road sensors and Video Image Processing (VIP)—to ensure full coverage and to quickly and accurately detect incidents and traffic queues. Upon detecting unexpected traffic conditions, the system automatically sends warning messages to two electronic signs in advance of the tunnel, notifying motorists of potentially unsafe conditions.

The system is also the first in the Ministry to use a browser-based user interface for monitoring and override control from the Traffic Operations Centre (TOC). Incidents are logged in the database with streaming digital video starting one minute before the actual incident occurs, and email notification of incidents and equipment status changes are sent out automatically.

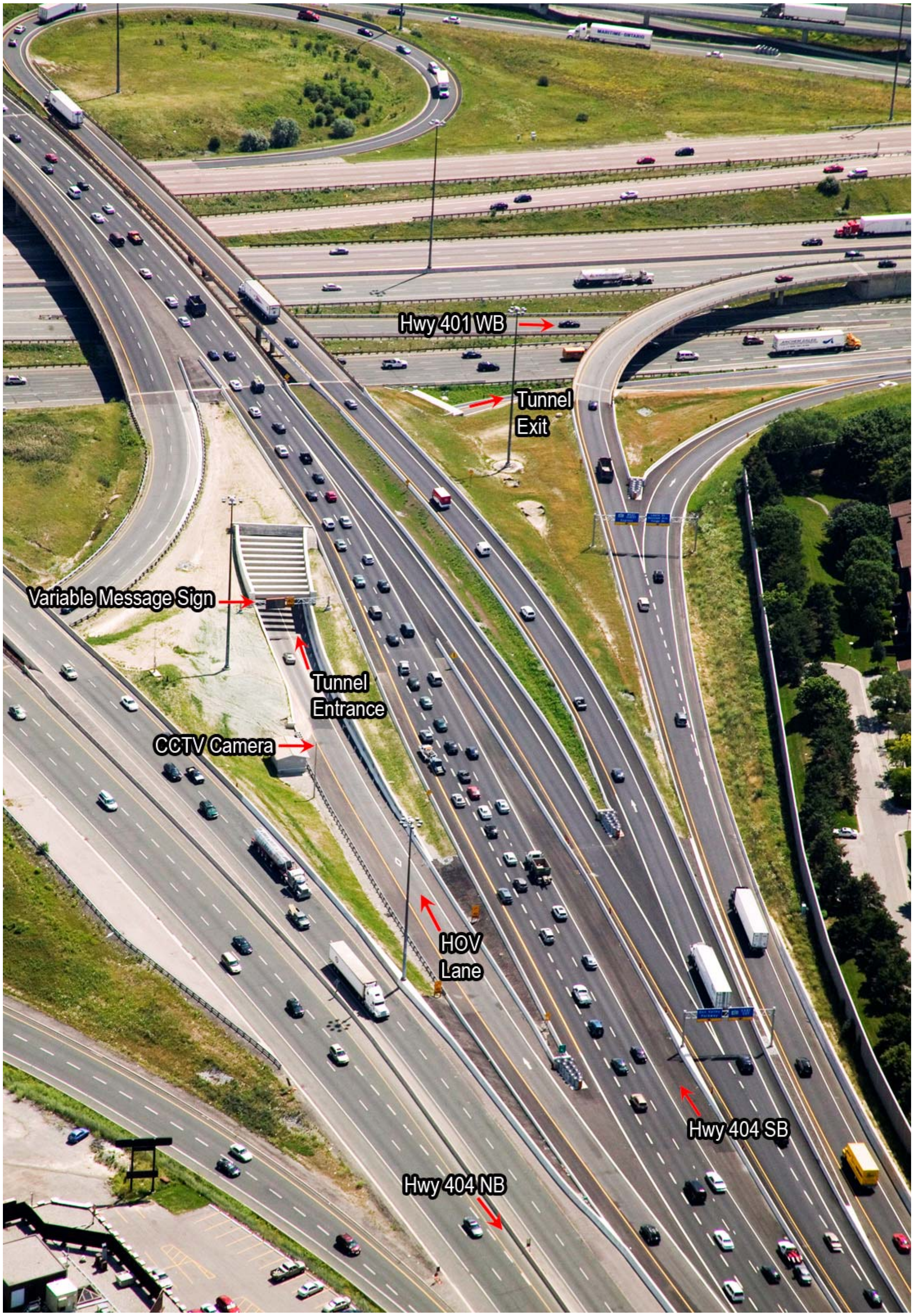

Figure 3 – Aerial View of Hwy 404 & Hwy 401 Interchange, July 2006

SYSTEM OVERVIEW

The Advance Warning System has an effective control area of about 400m including the 90m tunnel (**Figure 4**). The objective of the system is to detect traffic problems such as queues, stopped vehicles, debris, pedestrians, etc., accurately and quickly (i.e. with a response time of less than five seconds) along the HOV lane leading into and out of the tunnel. When a traffic problem is detected and an alarm is declared, the system automatically displays warning messages on two variable message signs to alert approaching motorists. The system is fully automatic, requiring no confirmation from an operator prior to sign activation. Using the same algorithm, the system also automatically removes the warning messages upon detected free-flow conditions.

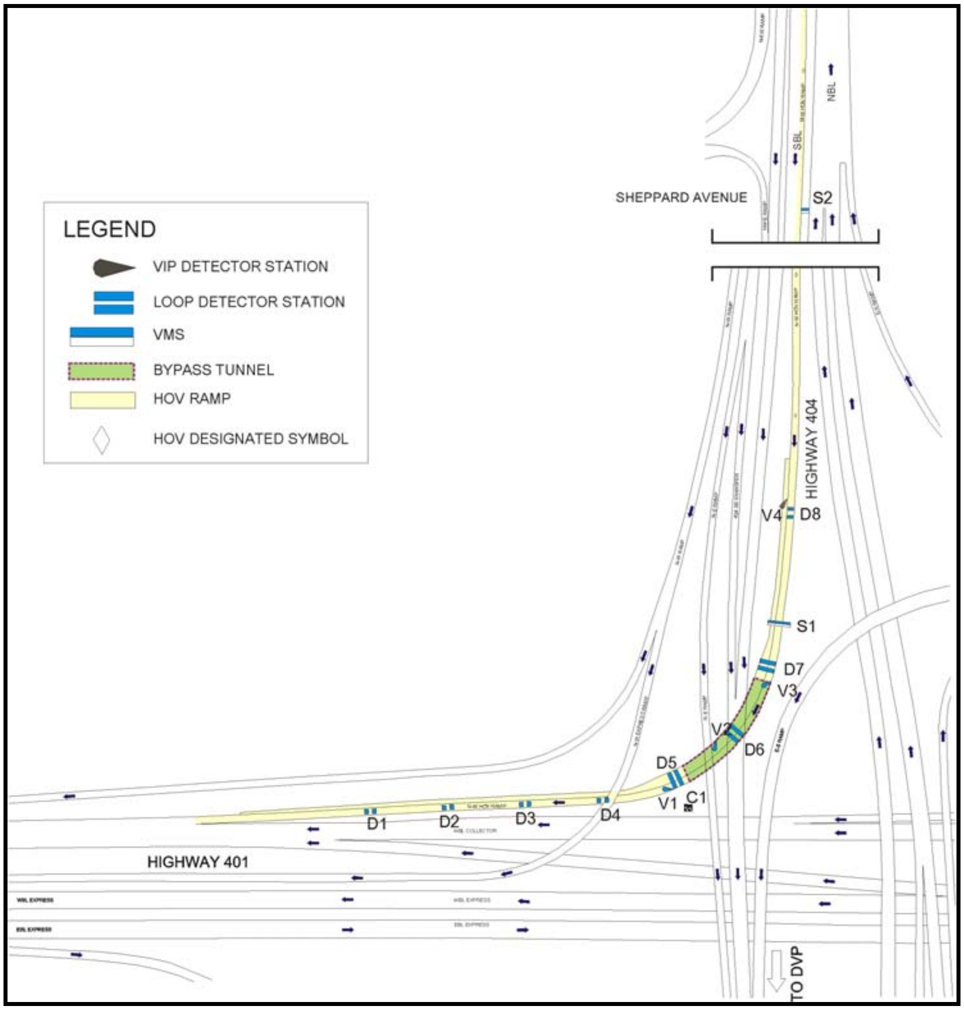

Figure 4 - Equipment Layout

An automated warning system requires high reliability and durability. The AWS was designed with built-in on-going diagnostics and logging, in a fully redundant, hot-standby computer configuration located at the tunnel within a roadside cabinet. The AWS design also enables full autonomous operation upon any failures in the communications link to AWS servers at the Ministry's COMPASS Traffic Operations Centre.

The major components of the system are the field equipment, Graphical User Interface (GUI), algorithms, and sign messages, which are described in more detailed in the subsequent sections.

Field Equipment

The AWS field equipment consists of eight double-loop Vehicle Detector Stations (VDS), four stationary colour Closed Circuit Television (CCTV) cameras, one Video Imaging Processing (VIP) analyzer, two Variable Message Signs (VMS), and two Advanced Traffic Controllers (ATC).

The eight double-loop Vehicle Detector Stations (VDS) are located before, within, and after the tunnel. A total of three VDS locations are spaced every 40 meters within the tunnel and the remaining five VDS are spaced from 50 to 100 meters outside the tunnel. All VDS within the tunnel use rectangular preformed loops installed below the tunnel's concrete floor and span from wall-to-wall to capture vehicles both within the lane and the right shoulder. The VDS outside the tunnel use MTO COMPASS standard diamond loops in the base asphalt centered within the lane. All VDS loops are connected to the AWS single roadside traffic cabinet and provide vehicle presence indications concurrently to two Advanced Traffic Controllers.

Figure 5 – CCTV Camera

A total of four stationary colour Closed Circuit Television (CCTV) cameras were installed to provide full visibility of the AWS control area. All cameras are stationary to meet the requirements of the VIP technology deployed. The camera at the tunnel approach is mounted on a concrete pole, and the remainder are mounted within the tunnel, as shown in **Figure 5**. Live video feeds from all cameras are transmitted to the COMPASS Traffic Operations Centre (TOC) via Ministry-owned fibre backbone using FM-modulation. All camera video feeds are concurrently available to both the VIP for automated incident detection and to operations staff 24 hours a day, 7 days a week for incident management and response.

The Video Imaging Processing (VIP) system provides enhanced real-time traffic incident detection and digital video recording, as shown in **Figure 6**. The VIP provides various incident detection alarms (e.g. stopped vehicle, vehicle driving the wrong way, etc) directly to the AWS for automated message display on the two AWS message signs without any operator confirmation.

The system has two NTCIP compliant 1203 v1 Variable Message Signs (VMS) utilizing NTCIP 2104 Ethernet subnet profile. Both VMSs are full matrix signs with 30 vertical rows by 56 horizontal columns of LED pixels. The VMS are installed to forewarn upstream vehicles of any queue or incident within the AWS control area. The first sign was installed on Highway 404 Southbound, 1 km upstream of the tunnel and the second sign was mounted at the entrance to the tunnel. MTO COMPASS operators are able to manually override the messages displayed on VMSs for incident management and divert traffic when the tunnel is closed for major incidents or maintenance.

Figure 6 – VIP Video Playback

Two Advanced Traffic Controllers (ATCs) were installed in the roadside AWS traffic control cabinet. Both controllers are connected concurrently to the central system, all loop and VIP dectectors, and other ancillary equipment. The first ATC acts as the primary day-to-day controller, while the second ATC acts as a hot standby with the same configuration, automatically taking over the primary operations within seconds of any primary controller failure. This dual ATC configuration provides fault tolerance to ensure a high AWS reliability and availability.

Ministry-owned fibre optic Ethernet LAN provides a high-speed reliable communication network to connect all AWS field devices and provides a link to MTO TOC for remote monitoring, override, and diagnostics. The fibre optic system is built using a fault tolerant ring topology.

Graphical User Interface

A user-friendly Graphical User Interface (GUI) was developed for Ministry's Traffic Operations Centre (TOC) operators and supervisors in order to perform equipment control, data management, and system monitoring. The GUI consists of a not-to-scale schematic map with interactive graphical icons representing the current state of equipment and traffic conditions (**Figure 7**). Different user levels allow the Ministry to assign appropriate staff access to different functions and features.

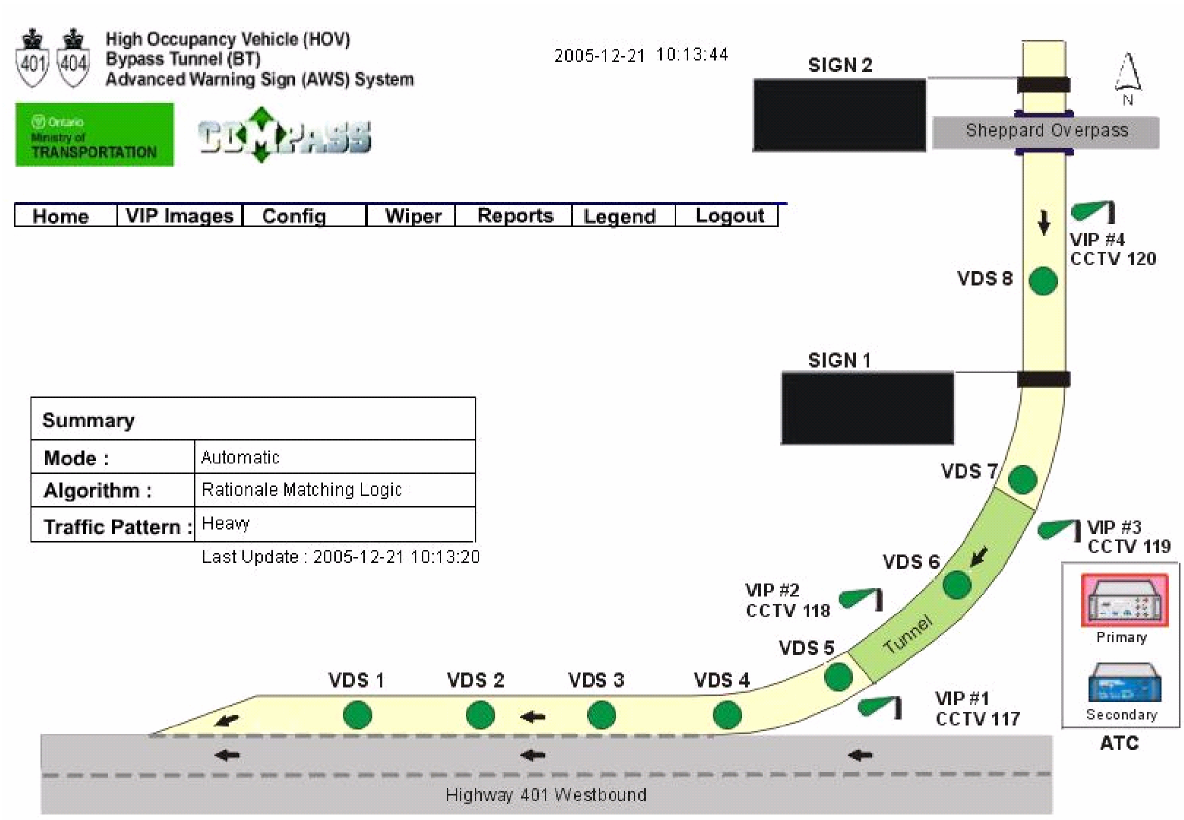

Figure 7 – Graphical User Interface

The AWS server uses the Java 2 Platform, Enterprise Edition (J2EE) in order to manage controls. Oracle 10g database and Oracle application servers support multiple browser-based GUIs. The Advanced Traffic Controllers located within the roadside traffic cabinet perform all critical AWS functionality. Upon VIP-detected incidents, the system transmits alarm messages to the controller to display the corresponding automatic sign messages.

The AWS server provides the following non-critical user and database functions:

- Monitor operations in real-time
- Graphically display on-going incidents, queues, VMS messages, and equipment status
- Upon receiving VIP alarms, trigger the designated cameras to record a short video clips and incident detections from the loops
- Override control of the VMSs by manually selecting sign message choices from the message library
- Enable and disable equipment such as VMS, loop and video detectors, etc.

- Display and modify the system configuration options including VMS messages
- Trigger CCTV wiper control for cleaning camera lenses
- Automatically disable the VIP camera detection function when the wiper is active
- Manage alarms and event notifications/confirmations to operators when the advance warning signs are activated and/or field equipment failures occur
- Log all events and five minute loop data into a database
- Retrieve all events and five minute loop data and generating customizable reports and logs
- Retrieve video files for playback

The online browser interface used to monitor and control the system allows for significantly improved maintenance. Maintenance staff can now view and diagnose potential equipment malfunctions remotely via the Ministry's secure private COMPASS LAN.

All incident notification and equipment status changes are automatically emailed to the appropriate operations and maintenance staff. This innovative approach reduces response times and provides an auditable system performance log. Furthermore, the system automatically digitally records incidents that have been detected. This allows the COMPASS Operators to better manage incidents and provide more detailed information to those who require it, such as emergency services.

Algorithms

Three algorithms, or computer programs, were developed and deployed on the ATC in order to effectively detect queues and incidents in different traffic conditions:

- *Rational Matching Logic* (heavy traffic detection)
- *Vehicle-Tracking Logic* (light traffic detection)
- *Traffic Pattern Selection Logic*

The system automatically operates with the *Rational Matching Logic* (i.e., a heavy traffic detection algorithm) during high volume hours (i.e. peak) then seamlessly switches to *Vehicle-Tracking Logic* (i.e., a light traffic detection algorithm) during light volumes (i.e. off-peak).

The third algorithm, *Traffic Pattern Selection Logic*, is used to constantly monitor the change of the traffic pattern throughout the peak and off-peak hours and determine the better detection logic to be used. **Figure 8** illustrates the process of the *Traffic Pattern Selection Logic*.

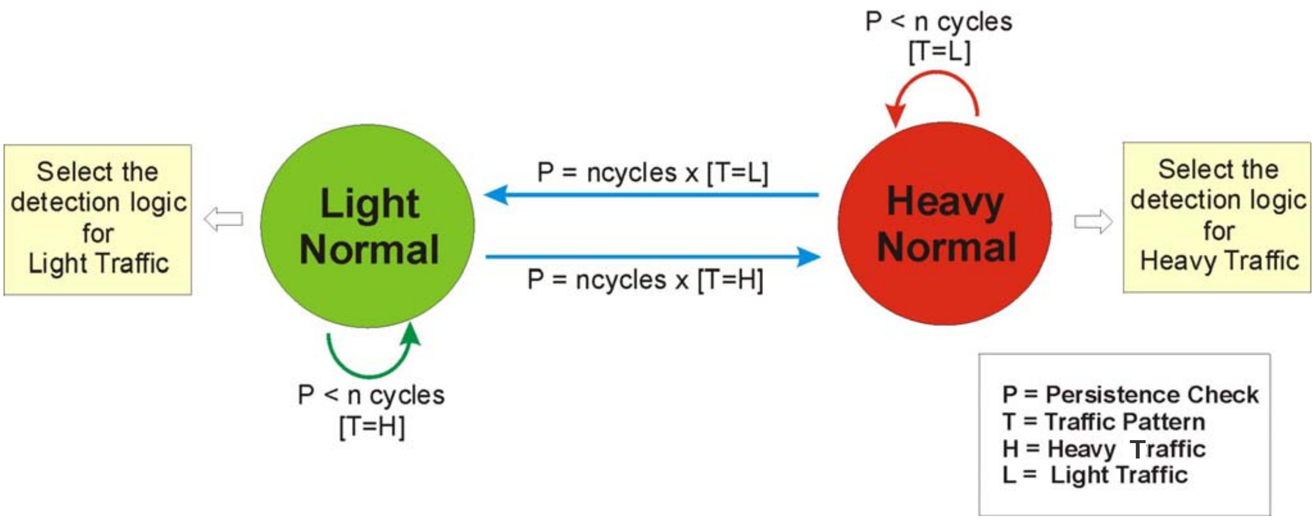

Figure 8 - Traffic Pattern Selection Logic Diagram [Source: Lee, Rex, et al., 2006]

As described previously, queue and incident detections in the tunnel are supported by both the loop detector and video detector technologies to enhance coverage and efficiency. A typical coverage area is shown in **Figure 9**.

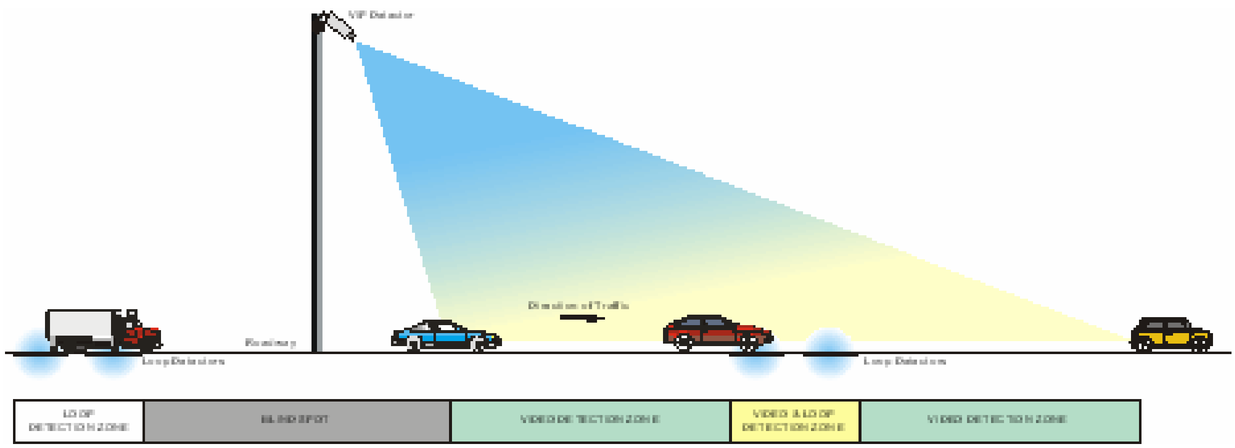

Figure 9 - Typical Detection Zone Classification [Source: Lee, Rex, et al., 2006]

This deployment of the VIP cameras by the Ministry is a pilot implementation intended to utilize and evaluate potential advantages of VIP technology. The video detection zone (i.e., green area in Figure 8) and overlapping video and loop detection zone (i.e., yellow area in Figure 8) provide superior detection. Blind spots (i.e., grey area) are minimized by strategically placing the video cameras within the tunnel.

Sign Messages

The AWS automatically displays and removes Variable Message Sign (VMS) messages on the two VMSs (**Figure 10**) based on the sign location in relation to the detected queue or incident. The AWS maps both VIP and loop detection zones to predefined warning messages. Currently, the following two-phase warning messages are used:

Figure 10 - Automatic Warning Message

"Prepare to Stop / Slow Traffic Ahead"

- OR -

"HOV Ramp to 401 West Collector / Traffic Moving Slowly"

The VMS displays a blank message when there is no queue or incident detected. Via the AWS user interface, MTO COMPASS operators can manually override automated warning messages by selecting predefined messages (e.g., "HOV RAMP TO 401 WEST COLLECTOR CLOSED") anytime based on the prevailing conditions of the tunnel.

INTEGRATION AND TESTING

Integration, evaluation, and system performance testing of the Advance Warning System (AWS) had to be completed before the tunnel was open to the public. Following factory acceptance testing of the AWS using traffic simulators, an existing highway-to-highway ramp with similar traffic patterns was selected as a real-world test site to ensure the system could be commissioned and integrated seamlessly.

The ramp test provided an opportunity to evaluate the system performance and identify any potential problems prior to final installation. The test confirmed the following aspects of the system to ensure smoother integration of the final system:

- End-to-end integration between field equipment, ATC controllers, and the central system
- Traffic data collection capability
- Verification of queue detection and clearance algorithms
- Verification of algorithm selection logic

The chosen test ramp was oriented parallel to the bypass tunnel, from Highway 404 Southbound to Highway 401 Westbound Collector. Three sets of loops and a single ATC controller were installed in the adjacent roadside cabinet to create a scaled-down AWS. The system parameters were continuously monitored for three months and eventually used as the initial settings for the bypass tunnel, although further parameter fine-tuning and software adjustment for the tunnel were required due to the different lane configuration, system operations, and driver behaviour.

Since the commencement of operations in December 2005, the system has been operating reliably. In the first few months of operations, the speed and occupancy algorithm thresholds were adjusted to match the live traffic conditions, e.g., filtering out buses that usually travel in a slower speed which can cause the system to think it is seeing short chains of slow moving vehicles. From the system logs, it was observed that the system operates consistently to raise alarm when appropriate.

In the heavy traffic algorithm, the system reacts responsively to slow moving vehicles and raises an alarm once slow traffic is detected. **Figure 11** shows a system log for the activation of the queue alarm in heavy traffic and the associated five minutes of data showing the slow traffic.

Date / Time	Event Type	Description of Activity
03/10/06 07:43:47	Zone Status	Zone 6 from CLEAR to INQUEUE
03/10/06 07:43:47	Queue Status	Queue Map .....Q..
03/10/06 07:44:02	Sign Status	Sign 1 aspect change from " "(1) to "PREPARE TO STOP SLOW TRAFFIC AHEAD"(2)
03/10/06 07:44:03	Sign Status	Sign 2 aspect change from " "(1) to "HOV RAMP TO 401WEST COLLECTOR TRAFFIC MOVING SLOWLY"(3)

						Vehicle Length Bins						Speed Bins												
Date / Time	Location	Occupancy	Headway	Volume	Speed	1	2	3	4	5	6	1	2	3	4	5	6	7	8	9	10	11	12	13
03/10/06 07:45:00	VDS 1	3%	9s	34v	65k	0	9	25	0	0	0	0	0	0	0	1	5	24	4	0	0	0	0	0
03/10/06 07:45:00	VDS 2	4%	9s	35v	61k	0	19	16	0	0	0	0	0	0	0	2	14	18	1	0	0	0	0	0
03/10/06 07:45:00	VDS 3	5%	9s	36v	53k	0	15	21	0	0	0	0	0	0	0	9	22	5	0	0	0	0	0	0
03/10/06 07:45:00	VDS 4	5%	8s	36v	49k	0	16	20	0	0	0	0	0	0	0	20	16	0	0	0	0	0	0	0
03/10/06 07:45:00	VDS 5	5%	8s	36v	43k	0	34	2	0	0	0	0	0	0	9	25	2	0	0	0	0	0	0	0
03/10/06 07:45:00	VDS 6	8%	8s	37v	33k	0	28	9	0	0	0	0	4	4	[illegible]	[illegible]	0	0	0	0	0	0	0	0
03/10/06 07:45:00	VDS 7	5%	8s	36v	41k	2	24	10	0	0	0	0	0	0	15	19	2	0	0	0	0	0	0	0
03/10/06 07:45:00	VDS 8	6%	8s	37v	53k	0	0	37	0	0	0	0	0	0	1	9	25	2	0	0	0	0	0	0

Figure 11 – System Log for heavy traffic algorithm [Source: Lee, Rex, et al., 2006]

In the light traffic algorithm, the system is also able to react promptly upon detection of "missing" cars between loop stations. **Figure 12** shows a system log for the activation of queue alarm in the light traffic algorithm and the associated five minutes of traffic data. There is a stopped vehicle between loop stations 6 and 7.

Date / Time	Event Type	Description of Activity
01/26/06 02:51:21	Zone Status	Zone 7 from CLEAR to INQUEUE
01/26/06 02:51:21	Queue Status	Queue Map ......Q.

						Vehicle Length Bins						Speed Bins												
Date / Time	Location	Occupancy	Headway	Volume	Speed	1	2	3	4	5	6	1	2	3	4	5	6	7	8	9	10	11	12	13
01/26/06 02:55:00	VDS 1	0%	2440s	1v	77k	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
01/26/06 02:55:00	VDS 2	0%	2440s	1v	70k	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
01/26/06 02:55:00	VDS 3	0%	2440s	1v	65k	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
01/26/06 02:55:00	VDS 4	0%	2441s	1v	65k	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
01/26/06 02:55:00	VDS 5	0%	2441s	1v	54k	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
01/26/06 02:55:00	VDS 6	0%	2443s	1v	50k	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
01/26/06 02:55:00	VDS 7	0%	0s	0v	0k	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
01/26/06 02:55:00	VDS 8	0%	2443s	1v	73k	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0

Figure 12 – System Log for light traffic algorithm [Source: Lee, Rex, et al., 2006]

The system demonstrates that, combined with the high accuracy of loop detectors, the algorithms perform effectively with a low false alarm rate in either light or heavy traffic conditions.

CONCLUSIONS

The Advance Warning System for the Highway 404 HOV tunnel provides the same or greater degree of motorist safety as a traditional freeway geometry reconfiguration at a fraction of the cost to the public. Furthermore, the technological solution improves the operational management of incidents within the tunnel via the addition of the automatic video-based incident detection system. Traffic problems can now be detected much more quickly and the digital video recording feature means more detailed information for incident response and analysis. Emergency services can now be notified sooner, potentially resulting in saved lives.

The AWS is designed to ensure that motorists are well aware of imminent congestion conditions or traffic problems in the tunnel, thereby minimizing rear-end collisions and secondary collisions. The system operates reliably and consistently with the light and heavy traffic algorithms based on loop technology, as well as with the seamlessly integrated off-the-shelf video detection equipment. The VIP cameras improve the AWS by detecting slow or stopped vehicles quicker and more effectively than traditional loops.

Since the commencement of operations on December 2005 to April 2008, more than 200 confirmed incidents have occurred within the Advance Warning System limits. Only one of these incidents was a single vehicle collision due to speeding. The system has been credited for significantly improving motorist safety and effectively reducing the potential for rear-end collisions.

The results to date and positive public response show that the key functions of the system—to detect traffic problems and provide advance warning—have been achieved.

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