Proceedings of the 1995 Winter Simulation Conference
ed. C. Alexopoulos, K. Kang, W. R. Lilegdon, and D. Goldsman

ENHANCED THOREAU TRAFFIC SIMULATION FOR INTELLIGENT TRANSPORTATION SYSTEMS (ITS)

Paul T. R. Wang
Richard A. Glassco

The MITRE Corporation
McLean, Virginia 22102, U.S.A.

ABSTRACT

Traffic and Highway Objects for Research, Analysis, and Understanding (THOREAU) is an object-oriented microscopic and mesoscopic traffic simulation tool for traffic engineers. It emphasizes the simulation of Advanced Traveler Information Systems (ATIS) and Advanced Traffic Management Systems (ATMS) as components of Intelligent Transportation Systems (ITS). This paper describes recent enhancements to THOREAU in the area of ATMS, namely the microsimulation of actuated signals and corridor-wide signal optimization in conjunction with route guidance and incident management. There are strong coupling effects among various trip time control parameters including signal cycle times, green wave offsets, and ATMS control strategies. Using sample urban traffic networks, the impacts of actuated signal controllers, the adaptive Webster-Cobbe algorithm for isolated intersection, traffic detector placement strategies, and coordinated corridor-wide optimization can be quantified. Consequently, traffic engineers may use THOREAU to explore alternative ITS technologies or architectures for optimal signal control and to validate network performance estimates obtained through analytic or rule-of-thumb approaches.

1 INTRODUCTION

THOREAU was designed in 1991 to model the emerging Intelligent Transportation Systems (ITS) technology. ITS is a multi-million dollar national program for improving urban, rural, and freeway transportation through the use of advanced computing, communications, sensor, and global and/or local flow control.

THOREAU can use either microscopic or mesoscopic traffic simulations to track individual trips from source nodes to destination nodes. Microscopic traffic simulations track vehicle speed, headway, offset, and lane shifts; while mesoscopic traffic simulations use flow density equation to track only link travel time from node to node.

Two major aspects of the ITS technologies are explicitly simulated in THOREAU: Advanced Traffic Management Systems (ATMS) and Advanced Traveler Information Systems (ATIS). For intelligent route guidance, shortest travel time paths are computed and followed by ATIS-equipped vehicles; while for ATMS simulation, signal control by fixed timing plans, actuation, and adaptive Webster-Cobbe algorithm at either isolated intersections or coordinated corridors are modeled.

The implementation of a modified Floyd algorithm for ATIS route guidance was presented in Niedringhaus and Wang (1993). This paper details recent enhancements to THOREAU for ATMS optimal signal control simulation, namely, the implementation of semi- and total actuated signal controllers and corridor-wide signal optimization.

2 ACTUATED SIGNALS SIMULATION

Previous versions of THOREAU simulated NEMA (Federal Highway Administration 1988) or Urban Traffic Control Systems (UTCS) (Kell and Fullerton 1991) signal controllers with a fixed timing plan. Multiple timing plans can be used to evaluate off-line signal optimization, for example, plans calculated by TRANSYT-7F. Typically, THOREAU simulates traditional UTCS fixed timing signal control under multiple cycle times, variable subphase splits, multiple intervals per subphase, and flexibe grouping of subphases.

A significant recent THOREAU enhancement is the simulation of both semi- and total actuated signal controllers. Actuated signals operating under controllers for isolated intersections are commonly used in arterial streets or for ramp meters. A brief discussion of the operation of actuated signal controllers is followed by an indication of how they are simulated by THOREAU.

For semi-actuated controllers, one or more detectors are required on the minor phase approaches (see Figure 1A). The major phase receives a minimum green that is extended indefinitely until it is interrupted by the detectors placed for the minor phase. The interrupted controller waits for the completion of its minimum green period in the major phase prior to a phase change. Once in the minor phase, the associated approaches receive a minimum green that may be extended by a fixed amount as incremental green periods if additional actuation occurs during the minor phase green period, subject to a preset maximum value. Once the minor phase exhausts its maximum green interval or there are no more actuations, the controller returns to its major phase. Any unfinished actuations are remembered and carried over to next cycle. Phase transition is preceded with preset yellow and all-red clearance.

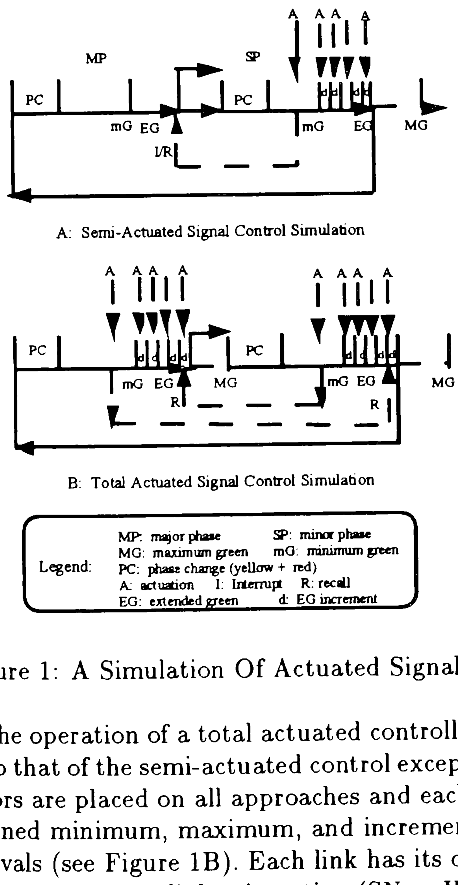

Figure 1: A Simulation Of Actuated Signal Control

The operation of a total actuated controller is similar to that of the semi-actuated control except that detectors are placed on all approaches and each phase is assigned minimum, maximum, and incremental green intervals (see Figure 1B). Each link has its own phase associated with its link orientation (SN or WE) and a cross phase (WE or SN) for traffic on the links crossing this link. Each phase is given its minimum green period that can be extended to reach the maximum green period if no actuation is detected by the detectors for the cross phase. Phase transitions occur either when the maximum green period has completed or when actuation is detected from detectors on the cross links. The later is determined by whether or not an incremental green value is defined for the current phase. At the end of each maximum green period, any outstanding actuation will be saved as recalls and carried over to next phase as new actuation. As in semi-actuated control, phase transition is preceded with preset yellow and all-red clearance.

In THOREAU actuated signal control is simulated with signal controller and detector objects. The controllers are defined by a SGNL input file that specifies controller type, signal control parameters such as minimum green time, maximum green time, and incremental green time for each phase, and the association of detectors to the controller. The controller objects set the signal colors as defined by the specified times subject to interrupts from detectors. Detectors can be placed anywhere in a link or lane before the approach to the intersection. Statistics collected by a detector include volume, occupancy, and the speed of the last detected vehicle. Thus, different ITS sensor technologies and various signal actuation parameters setting may be simulated to determine their impacts on traffic flow or inter-node travel time.

3 CORRIDOR OPTIMIZATION

Another recent enhancement toTHOREAU is the simulation of corridor travel time optimization. A corridor consists of an ordered sequence of links. Corridors are usually defined so that there is a significant volume of traffic traveling from the beginning link of the corridor to the end link. In THOREAU, links are one way arcs; multiple corridors are needed to define parallel traffic in the opposite direction. Signal controllers belonging to the same corridor may or may not operate under a common cycle time. If all the controllers within a corridor are synchronized to a common cycle time, it is referred to as a synchronized corridor. Synchronized corridors can maintain progressive green waves to alleviate congestion. A signal controller may belong to several corridors but green waves can only be maintained on one or two of the corridors to which the signal controller belongs.

During THOREAU initial setup time, the corridor free flow time (CFT) is computed for each corridor defined in the corridor input file. For each predefined corridor, a new measure of effectiveness (MOE), namely, the corridor congestion index (CCI), is computed at the beginning of every ATMS cycle. The

CCI is used to determine the critical corridor with the worst congestion. The CCI is computed as a weighted sum of end-to-end corridor travel time (the latest, running average, or predicted), queue length at intersections (total, maximum, or average), node stop time (total, maximum, or average), and a weighted sum of node volume-to-capacity ratios along the corridor. More specifically, CCI is computed by the following equation:

$$CCI = c_1 f_1(x) + c_2 f_2(y) + c_3 f_3(z) + c_4 f_4(u)$$

where

x = CTT: Corridor Travel Time (latest, average, or estimated)

y = CQL: Corridor Queue Length (total, average, or maximum)

z= CST: Corridor Node Stop Time (total, average, or maximum)

$u = VCR_i$: Volume Capacity Ratio at Node i for $1 \leq i \leq n$ (along the corridor)

$0 \leq c_1, c_2, c_3, c_4 \leq 1$ and $c_1 + c_2 + c_3 + c_4 = 1$

The parameterized CCI equation allows one to estimate the corridor congestion index under different corridor congestion measurements for different ITS designs such as different types of detectors. Using several different MOEs as the constituting elements for the CCI, one may determine the correlation among these MOEs and their impacts on corridor travel time optimization by changing the relative weights of each control parameter, c_i, in each separated simulation with the same traffic network setup and demand profile.

According to the Highway Capacity Manual (TRB National Research Council, 1994) the node volume/capacity ratio, VCR_i, may be approximated by $(v_i/s_i)/(g_i/C)$ where v_i is the actual flow rate in vehicles per hour (through the corridor at node i) , s_i is the saturated flow rate in vehicles per hour green, C is the cycle length, and g_i is the green time allocated to corridor traffic at node i.

Since CTT, CQL, CST, and VCR_i are different measurements with distinct units and ranges, the functions, f_1, f_2, f_3, and f_4 must provide an appropriate normalization process that will map each measurement onto a common range of interval, (α, β), with the boundary conditions $f_1(CFT) = f_2(0) = f_3(0) = f_4(0) = \alpha$ and $f_1(\infty) = f_2(\infty) = f_3(\infty) = f_4(1) = \beta$. In the initial implementation, we will choose the interval $(0,1)$ as (α, β) with the exception of f_4 for which a value bigger than 1 may be obtained. It is expected that the functions f_1, f_2, f_3, and f_4 are strongly correlated; hence, the proposed weighted sum approach for the CCI computation wil provide the necessary flexibility in choosing a wide range of alternatives to implement corridor wise travel time optimization. Many approximations to the functions f_1, f_2, f_3, and f_4 exist, in THOREAU, they are approximated as follows:

$$f_1 = (1 - CFT/x)$$

where x is the latest average, or estimated corridor travel time.

$$f_2 = y/MQL$$

where MQL is the maximum queue length, a scalar constant large enough to limit f_2 to 1. $y = \sum_{i=1}^{n} q_i$, (total) or $y = \max_{i=1}^{n}$ (maximum) or $y = \sum_{i=1}^{n} q_i wI$ (average) where q_i is the recorded queue length at intersection i along the corridor, and $w_i = v_i/(\sum_{j=1}^{n} v_j)$, and n is the number of intersections.

$$f_3 = z/yC$$

where C is the cycle time and $z = \sum_{i=1}^{n} d_i$ (total), or $z = \max_{i=1}^{n} d_i$ (maximum), or $z = \sum_{i=1}^{n} d_i w_i$ (average) where d_i is the recorded total node delay at intersection i along the corridor.

$$f_4 = \sum_{i=1}^{n} r_i w_i$$

where $r_i = (v_i C/g_i s_i)$ the node volume to capacity ratio.

The critical corridor, C^*, is the corridor with the worst CCI among the corridors with a given priority or the one with the worst CCI if no priority is given. Once C^* is determined, the Webster-Cobbe algorithm (Webster and Cobbe, 1966) is used to determine a new cycle time for the bottleneck intersection, i.e., the node with the worst critical queue length or volume to capacity ratio. Then all controllers in C^* are assigned that same cycle time, whereas their phase splits are computed separately to best serve individual intersections. The offset of each controller along the corridor C^* is set to achieve a progressive green wave given the current traffic flow rate (recall that, by definition, there is only one direction of traffic flow on a corridor).

The corridor signal controller optimization is repeated for all the remaining corridors that are disjoint to corridors already optimized until all corridors are processed. The remaining corridor fragments or isolated intersections may be operated in either fixed time, semi-actuated mode, total actuated mode, or the Webster-Cobbe algorithm mode as they are defined in the signal input file. Figure 2 illustrates the THOREAU adaptive ATMS algorithm based upon the corridor travel time optimization framework.

A graceful phase transition of cycle times for all the signal controllers operating asynchronously in a corridor to a synchronized corridor is simulated by a simple strategy as follows. First, the current cycle of the critical node, N^* , is completed as it is; however, the next cycle time is gradually extended or reduced to its new value according to specified staging parameters. For other nodes in the same corridor, the offsets corresponding to the desired green wave will be determined; transitions from existing cycle time to the target cycle time will be done by scaling the next cycle time to terminate at the correct time offset relative to the bottleneck node within the corridor. The adjustment is needed only once and will be equally distributed to all sub phases of the scaled cycle to follow. Figure 3 illustrates the cycle and phase transition from C to C^*.

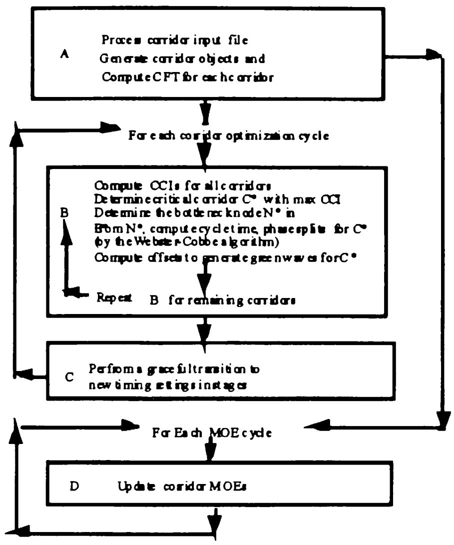

Figure 2: Adaptive Corridor Optimization

4 USER C-INTERFACE

Alternatively, THOREAU users may provide their own C procedure, UserProcCORI, via their own algorithm to determine the order, cycle times, phase splits, and offsets based upon the current corridor MOE data including, CTT, CQL, CST, and VCRi. A UserProcCORI user interface in C is given as follows:

```
ProcCORI (NoOfCorridors, CTTArray,
          CQLArray, CSTArray,
          LinkVolume, CrossVolume,
          VCRArray, LengthMatrix,
          CycleTimeArray, SplitAMatrix,
          SplitBMatrix, OffsetMatrix).
```

The user's corridor optimization procedure, UserProcCORI, will be called periodically at the end of each ATMS cycle if the ProcCORI keyword is present in the THOREAU master control file. The detailed input/output data structure for each argument in UserProcCORI procedure is explained in the THOREAU User Manual (Codelli, Glassco, et al. 1995).

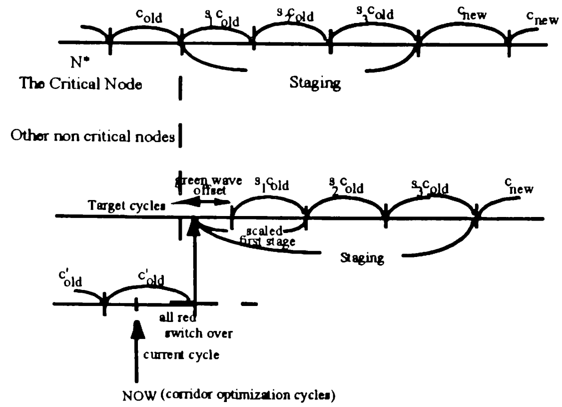

Figure 3: Ccyle Time and Phase Transition

5 TEST CASES

Test cases were constructed to demonstrate the validity of THOREAU micro simulation of ITS ATIS and ATMS technologies. First, urban traffic networks consisting of a number of corridors were constructed with fixed signal timing plans as baseline models. A set of THOREAU simulation control files were created to generate simulation sessions with selected ITS ATIS/ATMS options enabled or disabled. Each session simulated a unique ITS scenario with a set of ATIS and ATMS control parameters such as percent ATIS equipage, MOEs update frequency, mix of driver types, cycle times for ATIS or ATMS optimization. By enumerating an expected range of ITS control parameters, quantified MOE and trip time statistics were obtained for comparison and tradeoffs assessment. Figure 4 illustrates such an urban traffic network with 10 corridors (2 opposite corridors for each of the Pennysylvania Avenue and 19th Steet and 6 corridors for the ramaining one-way streets). A semi actuated signal controller was placed at the intersection of 21st and H Streets while a total actuated signal controller was placed at the intersection of 20th and H Streets to check out the simulation of actuated signal control. Actuated signal controllers operate independently with respect to corridor signal controller optimization. Five cases with 25 scenarios were simulated to determine the expected benefits as results of implementing some ATIS/ATMS alternatives.

Case 1 depicts the profile of a baseline model with fixed timing plan;

Case 2 depicts the profile of adaptive signal optimization using the Webster and Cobbe algorithm for individual intersections.

Case 3 depicts the profile of 50% ATIS equipage using the Floyd shortest path in travel time to route vehicles from the current link to the destination link.

Case 4 depicts the profile of coordinated corridor optimization for the critical corridor and bottleneck node.

Case 5 depicts the combined gain for all ITS options enabled; i.e., 50% ATIS equipage with corridor optimization and Webster-Cobbe optimization for isolated intersections.

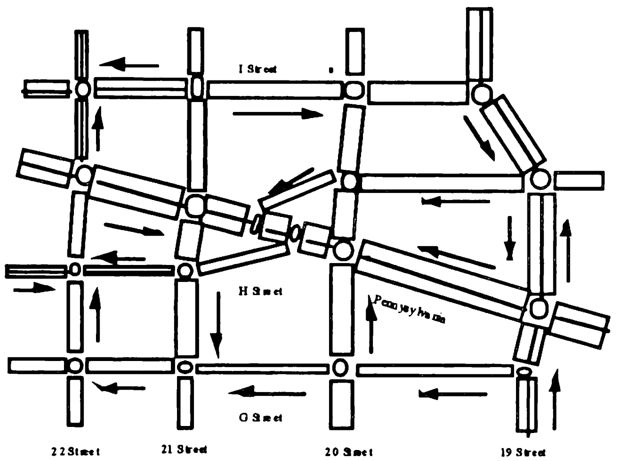

Figure 4: An Urban Traffic Network

In this example, MOE statistics were updated every 2 minutes with ATIS or ATMS control cycle times ranging from 30 sec to 300 sec for all cases. The average en route trip time excluding the queueing delay at source links are illustrated as Figure 5.

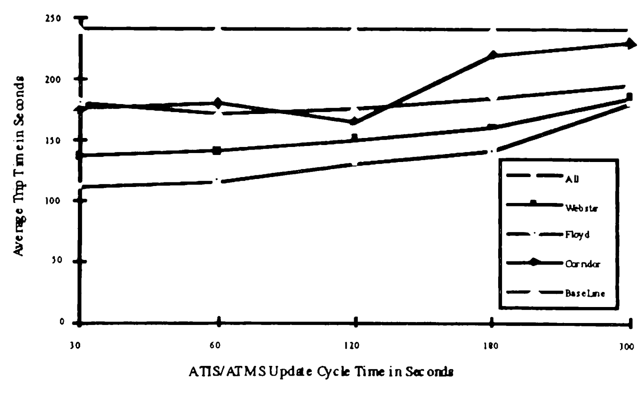

Figure 5: ITS Trip Time Reduction

From Figure 5, it is clear that individually, the Floyd algorithm for ATIS, the Webster-Cobbe algorithm for isolated intersections, or coordinated corridor optimization for ATMS does offer noticeable advantage over the baseline even on small scale urban traffic networks. The improvement (reduction) in average en route trip time also result in the increase of total number of trips completed in each simulation session and a decrease in network congestion as it is measured by the average number of uncompleted trips currently in a network. Table 1 illustrates the double gain in throughput and network capacity as result of selective ITS technology.

Table 1: Thruput Comparison with ITS Technology

ATMS/ATIS Options	Congestion as average number of vehicles in town					Thruput as total number of trips completed				
Cycle Time (sec)	30	60	120	180	300	30	60	120	180	300
BaseLine	23 8	238	238	23 8	23 8	298 9	29 89	298 9	29 89	29 89
Webster-Cobbe (ATMS)	14 2	139	142	14 4	177	33 83	334 7	33 84	325 5	32 10
Floyd (ATIS)	19 0	18 6	173	18 3	195	339 2	340 5	354 8	34 95	34 41
Corridor Optimization (ATMS)	20 4	21 5	179	22 8	22 9	323 8	310 6	32 95	30 69	314 0
Webster-Cobbe + Floyd + Corridor Optimization	115	11 5	127	125	177	375 2	364 6	35 65	367 5	32 10

Note: 40 minutes simulation, 50% equipage, 2 minute MOE data update cycles

Figure 5 also illustrates the coupling effects among different ITS technologies and cycle time controls. When ATIS or ATMS control information are updated periodically, the quality of the route guidance information and traffic flow data is critical to the expected quality of service of a given traffic network. Regional optimal cycle times for ATIS or ATMS alone may no longer be optimal when the two optimization techniques are combined together.

6 CONCLUSIONS

As an object-oriented simulation tool for urban and freeway traffic networks, THOREAU provides an ideal framework to derive quantified results on existing or emerging ITS technologies. THOREAU's features for the study of ATMS now include multi-functional traffic detectors, semi- and total actuated signal controllers, and corridor synchronization in addition to the Webster-Cobbe algorithm for isolated signal optimization. THOREAU can simulate these systmes with or without the Floyd algorithm for rout guidance.

Traffic engineers may use THOREAU to investigate a wide range of ITS architecture issues or optimization alternatives. Furthermore, THOREAU may be used to derive quantitative tradeoffs in trip time reduction, total throughput, and decrease in traffic congestion with or without roadway incidents. THOREAU may also be used to perform parametric study of signal actuation, detectors installation, and various control cycle evaluation. Such quantitative comparison are very helpful when performance can not be predicted or validated from other analytic approaches.

ACKNOWLEDGMENTS

The authors thank their colleagues, Mr. Michael McGurrin and Dr. Karl Wunderlich for their insights and suggestions. THOREAU was envisioned by McGurrin in 1991 as a new object-oriented traffic simulation tool for ITS technology. Over the years, McGurrin continues to supervise and support the development of THOREAU as MITRE sponsored research projects. THOREAU is now part of Government Furnished Materials (GFM) to the ITS architecture development team. Portion of this work was also supported by the Federal Highway Administration under a contract on ITS architecture development.

REFERENCES

Codelli, D. K. et al. 1995. *User's Manual for Traffic and Highway Object for REsearch, Analysis, and Understanding (THOREAU) Version 2.0*, Volume II, Revision 2, The MITRE Corporation.

Federal Highway Administration 1986. *TRANSYT-7F, Traffic Network Study Tool (Version 7F)*, Self Study Guide, U.S. Department of Transportation.

Federal Highway Administration 1988. *NEMA Microprocessor Controller Training Course*, FHWA-IP-86-4, U.S. Department of Transportation.

Federal Highway Administration 1992. *UTCS System Documentation: Volumes 1, 5, and 6*, Parking & Traffic Operations Bureau, City of Orlando, Florida.

Hunt, P. B. et al. 1981. *SCOOT - ATraffic Responsive Method of Coordinating Signals*, TRRL Laboratory Report 1014, Urban Networks Division, Traffic Engineering Department, Transport and Road Research Laboratory, Crowthorne, Berkshire.

Kell, J. H., and I. J. Fullerton. 1991. *Manual of Traffic Signal Design*, Institute of Transportation Engineers, New Jersey.

May, A. D. 1990. *Traffic Flow Fundamentals*, Englewood Cliffs, NJ: Prentice Hall.

Transportation Research Board 1994. *Highway Capacity Manual*, Special Report 209, Third Edition, TRB National Research Council, Washington, D. C.

Webster, F. V., and B. M. Cobbe. 1966. Traffic Signals, Road Research Tech. Paper No. 56, 55-60. Her Majesty's Stationery Office, Lodon, U.K.

AUTHOR BIOGRAPHIES

PAUL T. R. WANG graduated from National Cheng Kung University, Taiwan, China in 1966. He received an M.S. and a Ph.D. degrees in Computer and Information Sciences from The Ohio State University in 1973. From 1973 to 1983 he was with the General Electric Company, serving as a consulting engineer at the Information Services Division in Rockville, Maryland. Since 1983, he has been with the MITRE Corporation. Currently, he is a Lead Engineer at MITRE's IVHS site located at Washington D.C. His interests include optimization, simulation, modeling, and queueing theory. He is a member of InfORMS.

RICHARD A. GLASSCO completed a B.A. degree in Mathematics at Cornell University in 1976 and a M.S. degree in Operations Research at George Washington University in 1979. From 1976 to the present he has been employed as a consultant on modeling computer performance, surface and air traffic, telecommunications systems, and natural resource distribution. He has been a member of the technical staff at the MITRE Corporation since 1990 and currently supports ITS traffic simulation.