OPTIMIZING MASS TRANSIT UTILIZATION IN EMERGENCY EVACUATION OF CONGESTED URBAN AREAS

Hossam Abdelgawad and Baher Abdulhai, University of Toronto

Abstract

In this research we investigate how public transit systems can be optimally utilized to evacuate transit-dependent travelers in no-notice evacuation events. This paper presents how the capacity of mass transit can be optimally harnessed to alleviate congestion pressure during the evacuation of busy urban areas. The proposed model extends the traditional vehicle routing problem (VRP) to include *Multiple Depots* to better distribute the transit fleet, *Time Constraints* to account for the evacuation time window, and *Pickup and Delivery* locations of evacuees. The Multi-Depot Time-Constrained Pickup-Delivery VRP (MDTCPD-VRP) has been proven to be an NP-hard problem. ILOG, a Constraint Programming (CP) and Optimization platform, is used to model and solve the problem. The evacuation optimization process is divided into two stages; building the model using ILOG Dispatcher™ and solving the problem using ILOG Solver™. The problem is modeled and extended using the C++ libraries in Dispatcher and Solver. To quantify traffic congestion, a dynamic traffic assignment is performed first to generate the travel time characteristics on the network links for a hypothetical evacuation event in the core of Downtown Toronto. Bus routing, sequence of evacuees pickup, and departure and arrival times are presented.

Introduction

Emergency evacuation planning has drawn significant interest and attention over the past few years. The increasing rate of man-made disasters and natural catastrophes affecting major urban areas requires comprehensive analysis and planning for emergency evacuation scenarios. In this research we investigate how public transit vehicles can be utilized to evacuate transit-dependent travelers in no-notice evacuation events. Non-notice evacuation events come with little to no warning to transportation managers and the population. In this research, we demonstrate how the capacity of mass transit can be optimally harnessed to alleviate congestion pressure during the evacuation of busy urban areas. We extend the traditional vehicle routing problem (VRP) to include *Multiple Depots* to better distribute the transit fleet, *Time Constraints* to account for the evacuation time window, and *Pickup and Delivery* locations of evacuees. The Multi-Depot Time-Constrained Pickup-Delivery VRP (MDTCPD-VRP) has been proven to be an NP-hard problem. We also highlight the analogy between the traditional VRP and the MDTCPD-VRP in which customers are the evacuees, pickup points are hazard areas to be evacuated, delivery points are safe shelters, and vehicles are transit shuttle buses. ILOG Dispatcher™ and Solver™ are used to model and solve the problem, respectively. To quantify traffic congestion, a dynamic traffic assignment is performed first to generate the travel time characteristics on the network links for a hypothetical evacuation event in the core of Downtown Toronto.

This paper starts with brief review of the relevant literature on the VRP and its application in emergency evacuation. We then define the MDTCPD-VRP and present the constraint programming solution algorithm implementation in ILOG. The experimental design of the case study is then demonstrated. Evacuation strategies and scenario design are proposed and the model results are presented. We offer our interpretation of the findings, and our conclusions.

Literature Review

The vehicle routing problem (VRP) is a generic class of problems in which sets of customers are visited by vehicles. The goal is to solve the routing problem by assigning vehicles to traverse the network so as to visit customers, to meet given constraints, and to optimize certain objective functions. Therefore, the vehicle routing problem comprises several interacting elements. The following is a summary for these elements with the likely attributes of each element

- Customers: demand, time constraint, pickup and delivery location, priority
- Vehicles: capacity, cost, time window of vehicles
- Depot: number, location, capacity
- Network: travel time, distance, geographical representation

The VRP has been extensively studied in the literature. Numerous techniques are found with the common goal of modelling and solving the VRP; however, the solution procedures differ significantly according to the exactness of the solution and the problem size. Therefore, this review is limited to include the most relevant studies.

- ***VRP and Emergency Evacuation***

VRP is a cross-disciplinary problem in which efficient transportation is the core most of the applications. Desaulniers *et al.* (1998) presented a multiple depot vehicle routing problem with time windows to model and solve the urban bus scheduling problem (UBSP) and freight transport scheduling problem (FTSP). They formulated the problem as an integer nonlinear multi-commodity network flow model with time variables. The problem is solved using a column generation approach embedded in a branch-and-bound framework. The problem is solved using an approximate and optimal heuristics to find the optimal routing plan; however, the size of the problem was quite small and the maximum number of tasks that the algorithm can efficiently handle is 600. Sayyady F. (2007) investigated the use of public transit system in non-notice evacuations in urban areas. The author formulated the public transit routing plan

(PTRP) problem as a mixed integer linear program in which a network flow problem is solved with the objective of evacuating as much people as possible from a set of source nodes, representing transit stations, to a set of exit nodes representing shelters in a given time frame without violating the capacity constraints of the system. However, the bus schedules were predefined with a very limited number of tasks to be performed. The evacuation demand was assumed to follow a normal distribution in order to form the demand at each visit. This study provides sensitivity analysis to percentage of people relaying on transit and available fleet size. The author compares the computation time of two solution algorithms; CPLEX and Tabu Search. The computation was a bottleneck though. CPLEX runs out of memory after running for 3 days without reporting the optimal solution. The running time to evacuate 300 to 2000 people ranges from 166 to 167 min using CPLEX and 4 to 16 min using Tabu Search, respectively.

Pagès *et al.* (2006) introduced the mass transport vehicle routing problem (MTVRP) in which a fleet of vehicles (of given capacity) is routed to pick up and deliver passengers. The problem is solved iteratively between two levels; the Transit Problem (TP) and the Passenger Problem (PP). The TP is solved once to generate an initial solution and then the PP works on improving the first solution by assigning passengers to routes. The authors compared the computation time of CPLEX to the PP for different network sizes (5 to 56 links). The benefits of using PP are bigger in case of large networks. However, the network size and the problem dimensions are quite small compared to real life evacuation scenarios. Murray and Mahmassani (2003) provided two linear integer programs to express the household behavior in evacuation conditions. The first formulation determines the meeting location for the household members, while the second formulation deals with a modified version of the VRP in which the authors determine the sequence of family members pick up. Alshalalfah and Shalaby (2008) developed routing and scheduling algorithm for fixed-route and demand-responsive services in which the problem is formulated as extended VRP with additional constraints on customers pickup locations and their time widows. A constraint programming technique was used to solve the routing and scheduling problem.

Problem Definition

As previously mentioned, the VRP assigns a set of limited capacity vehicles to set of customers by building set of routes. The aim is to minimize the global cost of these routes (e.g., travel time) subject to capacity and time constraints. Solving the VRP has two stages; firstly, solving an assignment problem of whether to assign a particular visit to a given vehicle and secondly, a minimum path flow problem, in which each vehicle has to visit set of customers (points) using the optimal route (least cost route).

The traditional VRP is extended in our application to include the following:

- Pickup and Delivery Problem (PDP) where evacuees (customers) are picked up from hazard zones and delivered to shelters (safe destination) (within the same route) and then the vehicles (shuttle buses) head back empty to pick up more evacuees and so on until all the customers are delivered to shelters.
- Multiple Depots VRP (MDVRP) where the transit fleet is stored at multiple locations as opposed to the traditional fixed one depot location.
- Time Constrained Problem (known as VRP with Time Windows, VRPTW). Time window problems occur in many business sectors. The more the time constrains introduced to the problem, the more challenging is the routing plan. The

following time windows are modeled in the evacuation problem:

- Evacuees have to be picked up before a time threshold ($T_{MaxPickupTime}$)
- Evacuees have to delivered to safe destination before a time threshold ($T_{MaxDeliveryTime}$)
- Vehicles are available within certain period of time for operation ($T_{StartVeh}$, T_{EndVeh})

Modelling the VRP objective and cost might vary depending on the problem nature. In the literature, no unique objective function was used. Each application has its cost function that satisfies the problem-specific objective. In the study we limit the scope of the objective function to minimize the cost of the routing plan by summing the costs for all vehicle routings (total travel time).

Constraint Programming and Solving the MDTCPD-VRP

Constraint programming (CP) aims to simultaneously solve a constraint satisfaction problem (CSP) and an optimization problem. CP uses multiple algorithms to find feasible solution to constraint satisfaction and optimization problems. In CP problems, users are required to build a search strategy that describes how the decision variable values would change with iterations to satisfy the constraints.

Each decision variable in the CSP has its domain. A domain reduction algorithm works to remove the values form the domain of a variable that are apart from any feasible solution. This process is performed for all the variables in each constraint in the problem. At some point, the algorithm might discover that eliminating some values from the variable domain leads to an infeasible solution; at this stage the previous domain value is retrieved.

Constraint propagation deals with how the domain reduction technique is conducted among several constraints. Dealing with several constraints that have multiple variables in common is referred to as propagation of domain reduction among the constraints

Constraint programming systems (e.g., OPL and ILOG) are capable of providing comprehensive libraries of predefined and user-defined constraints, with associated propagation and domain reduction algorithms; therefore, it is often not necessary to create new constraints with specialized propagation and domain reduction algorithms. Moreover, new constraints can be added to the mix in an elegant way which is essential to ensure the extendibility and transferability of the model. ILOG, as Constraint Programming and Optimization system, tends to perform well on applications where domain reduction and constraint propagation are interacting effectively as search strategies, which is the case in routing and scheduling of emergency vehicles.

To solve the routing and scheduling problem in ILOG, two stages are performed. Firstly, building the model and secondly solving the problem. Building the model is conducted using ILOG Dispatcher^{TM} and solving the problem is performed using ILOG Solver^{TM}. Both Dispatcher and Solver are C++ libraries software from ILOG Inc. ILOG Dispatcher offers features especially adopted to solve vehicle routing and scheduling problems in which particular classes of objects are designed, such as vehicles, visits, nodes, dimensions, and constraints. ILOG Solver uses search strategies and constraint propagation to explore solutions to the optimization.

Experimental Design

Study Area

A hypothetical evacuation scenario for a very busy and dense part of Downtown Toronto, the financial district, is used as a case study in this investigation. This area is the economic hub of Canada. It is the most densely built-up area in Toronto, which has around 100,000 commuters entering and leaving the financial district every working day. Therefore, it is perhaps the most difficult to evacuate in the case of an emergency. Evacuation is assumed to occur mid-day in the early afternoon which is the worst case scenario to evacuate as most commuters will be at work.

Network Coding and Evacuation Demand

The transportation analysis zones (TAZs) defined for the study area are based on the Transportation Tomorrow Survey (DMG, 2006) and the City of Toronto data. Evacuation demand is estimated to be the reverse of the morning (6- 9 a.m.) arrivals of a regular week day to the Downtown core which results in 47,000 transit trips and 20,000 vehicle trips to be evacuated. Transit trips include auto passenger, transit excluding GO rail, cycle, taxi passenger, walk, and Joint GO rail and public transit trips. As illustrated in Figure 1, The GTA (Greater Toronto Area) zoning system is used to geographically distribute the evacuation demand to specific pickup points. We define the maximum acceptable walking distance for evacuees with respect to each zone centroid. In general, it was found that around 60% of transit users in Toronto live within 300 m airline distance from the transit stop (Alshalalfah and Shalaby, 2007). Also, transit users are unlikely to walk more than 400 m to a transit stop. Therefore, the following procedure is applied:

- Zone centroids are defined for each evacuation zone from which the demand is generated.
- If zones corners are within 400 m from the zone centroids, passengers are picked up at the 4 corners of the zones. Zones

larger than 800 x 800 m^2 are divided into subzones smaller than 800 m in diameter.

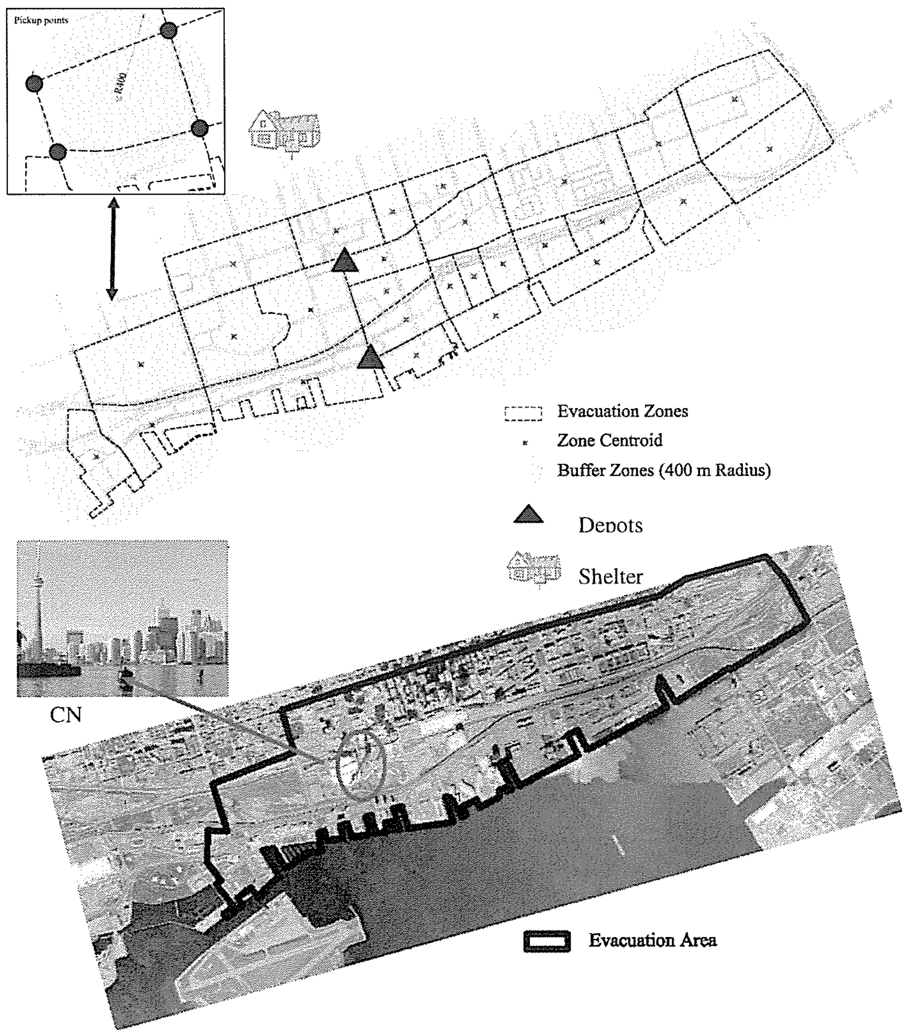

Figure 1: Transportation Network, Evacuation Zones, and Pickup Points

The network consists of 495 links and 558 nodes of which 54 are pick up locations.

Evacuation Strategies and Scenario Design

Proposed methods for improving the efficiency of emergency evacuation include reversing lanes in the direction of evacuation (contra-flow), staging the evacuation demand, destination choice optimization (i.e., returning home is not a priority), optimally controlling traffic, and providing route guidance to the evacuees. In this paper, we extend the work done on optimal spatio-temporal evacuation, OSTE, (Abdelgawad and Abdulhai, 2009) to include transit vehicles to evacuate the transit-dependent population in addition to the vehicular traffic. OSTE integrates demand scheduling and destination choice, in which we dynamically route traffic during evacuation, capture the dynamics of both the loading and the evacuation profiles with time, and provide evacuees with optimal spatio-temporal guidance throughout the emergency evacuation process. In other words, the background traffic is optimized and its output is used to form the travel cost in the proposed MDTCPD-VRP.

The disaster is assumed to happen at time 0, which requires the no-notice evacuation to begin immediately. In this scenario, there are 54 pickup points with total demand of 47000 evacuees and 20,000 vehicular traffic. We assume an available fleet of 50 shuttle buses each with capacity of 50 passengers. Shuttle buses are assumed to be stored at two depots as shown in Figure 1. Evacuees have to be picked before 120 minutes and have to be delivered to safe shelters (see figure 1) before 300 min, both measured from the onset of the evacuation event.

Model Results and Analysis

We demonstrate the optimal scheduling and routing for the shuttle buses for the proposed evacuation scenario. In service of space we show only an example for the model output in table 1. As shown in table 1, the arrival and departure times of buses at each visit are extracted and the associated travel time and distance travelled. Optimal transit routes are illustrated as a sequence of nodes starting from the last visit and ending at the shelters. For example, the first vehicle starts from Depot 1 at time 0 (node 483300), picks up 50 passengers (visit 879), and travels through the optimal route 2016, 482300, 472300 - - , etc. The vehicle then drops off the evacuees at shelter (node 23300) and continues to pick up more evacuees located at visit 76 after 5.37 min from the start of the evacuation. The routing and scheduling plan continues until all vehicles accomplish the assigned tasks. At the end of the evacuation, all vehicles return back to shelters as shown in the last row of table 1.In table 1, we show only one vehicle (the first assigned vehicle).

The network clearance time is found to be 124 min, i.e. the time at which the last evacuee reaches safe destination. The average trip time, i.e., from the time the person is picked up to the shelter is found to be 5.02 minutes. On the other hand, the average travel time to evacuate the background vehicular traffic is found to be 18 min with a network clearance time of 300 min.

Performed Visit	Arrival Time (min)	Departure Time (min)	Evacuees on Board	Travel Time (min)	Distance Travelled (m)	Trip													
visit879	0.00	2.38	50	0	0	Depot	483300	2016	482300	472300	-	-	shelter	531100	531	38300	-	-	visit76
visit76	5.37	7.74	50	5.36839	2292.71	visit76	27300	48	50	1926	-	-	shelter	531100	531	38300	-	-	visit102
visit102	9.91	12.29	50	4.54301	1888.54	visit102	27300	48	50	1926	-	-	shelter	531100	531	38300	-	-	visit128
visit128	14.45	16.83	50	4.543	1888.54	visit128	27300	48	50	1926	-	-	shelter	531100	531	38300	-	-	visit391
visit391	19.49	21.86	50	5.031	2432.91	visit391	533	73300	72300	41300	-	-	shelter	531100	531	38300	-	-	visit540
visit540	24.40	26.78	50	4.9189	2427.7	visit540	76300	77300	73300	72300	-	-	shelter	531100	531	38300	-	-	visit561
visit561	29.48	31.85	50	5.0734	2571.6	visit561	76300	77300	73300	72300	-	-	shelter	531100	531	38300	-	-	visit582
visit582	34.55	36.93	50	5.0733	2571.6	visit582	76300	77300	73300	72300	-	-	shelter	531100	531	38300	-	-	visit623
visit623	39.86	42.24	50	5.3116	2838	visit623	78300	77300	73300	72300	-	-	shelter	531100	531	38300	-	-	visit643
visit643	45.14	47.51	50	5.2759	2894.7	visit643	78300	77300	73300	72300	-	-	shelter	531100	531	38300	-	-	visit663
visit663	50.41	52.79	50	5.2759	2894.7	visit663	78300	77300	73300	72300	-	-	shelter	531100	531	38300	-	-	visit884
visit884	55.79	58.17	50	5.3793	3377.5	visit884	281	566	1185	280	-	-	shelter	531100	531	38300	-	-	visit726
visit726	63.22	65.59	50	7.4243	4164.5	visit726	217300	216300	215300	133300	-	-	shelter	531100	531	38300	-	-	visit929
visit929	69.35	71.73	50	6.1361	3789.5	visit929	566	1185	280	279	-	-	shelter	531100	531	38300	-	-	visit928
visit928	76.34	78.72	50	6.9864	4385.8	visit928	566	1185	280	279	-	-	shelter	531100	531	38300	-	-	visit415
visit415	82.24	84.62	50	5.9023	3091.6	visit415	57	56	52	45300	-	-	shelter	531100	531	38300	-	-	visit443
visit443	86.28	88.65	50	4.0344	1633.4	visit443	57	56	52	45300	-	-	shelter	531100	531	38300	-	-	visit193
visit193	90.56	92.93	50	4.2796	1912.9	visit193	75300	502300	57	56	-	-	shelter	531100	531	38300	-	-	visit43
visit43	94.90	97.27	50	4.3414	1960.5	visit43	27300	48	50	1926	-	-	shelter	-	-	-	-	-	shelter
Shelter	98.40	98.40	0	3.502	1.127	Shelter	23300												

Table 1: Example of Routing and Scheduling for Transit Vehicles

Summary, Conclusions, and Future Directions

In this study, a model for the *Multiple Depot Time Constrained Pickup and Delivery- VRP* is presented. This work extends the scope of the VRP compared to the literature. First, we eliminate the constraint of locating all the vehicles at one single depot; vehicles are rather distributed over two depots for illustration. Second, time constrains are modeled to account for the allowable window to pick up evacuees. Third, to quantify traffic congestion, a dynamic traffic assignment is performed first to generate the travel time characteristics on the network links. Fourth, we apply the model to a real life and relatively large network compared to the hypothetical test cases conducted in the literature.

The MDTCPD–VRP is modeled and solved using constraint propagation and optimization techniques. ILOG Dispatcher and Solver are used to model and solve the problem simultaneously in a very efficient computation time. In a Dual Core CPU with 2 GB of RAM, it took around 5 minutes to solve the problem for the shown network. The model output shows very detailed routing and scheduling plans which can be easily disseminated to evacuees in case of emergency evacuation.

The model is capable of handling evacuees waiting time costs and cost associated with using vehicles so as to minimize the waiting and the vehicle cost of the routing plan. Modelling multi-objective VRP with time constraints and multiple depots is deferred to future research. Also, further investigation is required to account for the optimal composition of transit vehicles and vehicular traffic in case of emergency evacuation. Moreover, alternative delivery sites where shuttle buses will seek the optimal destination would be investigated.

Acknowledgements

The authors gratefully acknowledge the financial support of the Connaught Fellowship of the University of Toronto, NSERC, and the Canada Research Chairs program. Travel demand data were provided by the University of Toronto Urban Transportation Research and Advancement Centre (UTRAC). This research was enabled by the Toronto Intelligent Transportation Systems Centre. The methodology and results presented in this paper reflect the views of the authors only.

References

Guy Desaulniers G. Lavigne J, and Soumis F. Theory and Methodology Multi-Depot Vehicle Scheduling Problems with Time Windows and Waiting Costs. European Journal of Operational Research 111 (1998), pp. 479–494.

Sayyady F. (2007) Optimizing the Use of Public Transit System in No-Notice Evacuations in Urban Areas. Thesis, Mississippi State University Department of Industrial and Systems Engineering.

Pagès L., Jayakrishnan R., and. Cortés C. Real-Time Mass Passenger Transport Network Optimization Problems. Transportation Research Record: Journal of the Transportation Research Board, No. 1964, Transportation Research Board of the National Academies, Washington, D.C., 2006, pp. 229–237.

Murray-Tuite P.and. Mahmassani H. Model of Household Trip-Chain Sequencing in Emergency Evacuation. Transportation Research Record: Journal of the Transportation Research Board, No. 1831, Transportation Research Board of the National Academies, Washington, D.C., 2003, pp. 21–29.

Alshalalfah B, and Shalaby A. Sensitivity of Flex-Route Transit Service to Design and Schedule- Building Characteristics.

Transportation Research Board of the National Academies, Annual Meeting CD-ROM, Washington, D.C., 2008.

Alshalalfah B. and Shalaby A. Case Study: Relationship of Walk Access Distance to Transit with Service, Travel, and Personal Characteristics. Journal of Urban Planning and Development, Vol. 133, No. 2, June 2007, pp. 114-118.

Data Management Group (2006) Transportation Tomorrow Survey: Travel Survey Summaries for the Greater Toronto Area. Joint Program in Transportation, University of Toronto, 2006.

Abdelgawad H.and Abdulahi, B. "Optimal Spatio-Temporal Evacuation Demand Management: Methodology and Case Study in Toronto". Poster Presentation in the Transportation Research Board of the National Academics, Washington, D.C, 2009.