A Decision Support Tool to Assess Importance of Transportation Facilities

Final Report

PREPARED FOR

REGION 2 - UNIVERSITY TRANSPORTATION RESEARCH CENTER

BY

RENSSELAER POLYTECHNIC INSTITUTE

AND

UNIVERSITY OF PUERTO RICO AT MAYAGUEZ

2008

Authored by: Satish Ukkusuri , Assistant Professor, Rensselaer Polytechnic Institute
Didier Valdes, Associate Professor, University of Puerto Rico at Mayagüez
Wilfredo Yushimito, Ph.D. Candidate, Rensselaer Polytechnic Institute

Disclaimer Statement

TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle A Decision Support Tool to Assess Importance of Transportation Facilities		5. Report Date October 2008
		6. Performing Organization Code
7. Author(s) Satish Ukkusuri (PI), Didier Valdes, Wilfredo Yushimito		8. Performing Organization Report No. RF 49777-20-04
9. Performing Organization Name and Address Rensselaer Polytechnic Institute, 110 8th St. Troy, NY 12180 University of Puerto Rico, PO Box 9000, Mayagüez, P.R. 00681		10. Work Unit No.
		11. Contract or Grant No.
12. Sponsoring Agency Name and Address University Transportation Research Center – Region 2 138th Street and Convent Avenue, NYC, NY 10031		13. Type of Report and Period Covered Final Report
		14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

Assessing the importance of transportation facilities is an increasingly growing topic of interest to federal and state transportation agencies. This work proposes an optimization based model that uses concepts and techniques of complex networks science to assess the importance of transportation facilities.

The criticality is addressed using an economic quantitative measure – the impact on total travel time by examining the negative effect on travel time if the facility is destroyed or disrupted accounting for changes in user decisions consequent to the disruption.

We developed an application using TransCAD's GISDK language and we present the results in a built-up network to assess the criticality of the major infrastructures that are used to access Manhattan in an AM peak hour.

17. Key Words Critical infrastructure, Travel Time,		18. Distribution Statement	
19. Security Classif (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No of Pages 56	22. Price

Form DOT F 1700.7 (8-69)

A Decision Support Tool to Assess Importance of Transportation Facilities

Final Report

Chapter 1 Summary

Assessing the importance of transportation facilities is an increasingly growing topic of interest to federal and state transportation agencies. In the wake of recent terrorist attacks and recurring manmade and natural disasters, significant steps are needed to improve security at both state and metropolitan level.

This project is the final deliverable and contains:

- An extensive literature review of related topics.
- A criticality measure for assessing the criticality of infrastructure measure based on complex networks science techniques.
- A macro for computing this measure under TransCAD.
- A detailed explanation of the implementation platform and a user manual.
- An example demonstration of the methodology on the New York City network.

Chapter 2 Table of Contents

Chapter 3 List of Figures

Chapter 4 CHAPTER 1: LITERATURE REVIEW AND OVERALL EVALUATION OF CURRENT METHODOLOGIES

This literature review summarizes the findings of relevant research and publications related to the project. The review is broadly divided into three parts. The first part addresses the different definitions of assessing importance currently used in literature (with an emphasis on NCHRP reports) and the second part reviews modeling and analytical tools used to address the problem of finding important nodes and links in a network. Specific examples of applications in transportation are provided in the third part.

1.1 Alternative Definitions and Measures of Importance

Post 9-11, there have been several publications by the National Cooperative Highway Research Program (NCHRP Reports 20-07, 525), Department of Homeland Security (National Infrastructure Protection Plan (NIPP)), and AASHTO (Ham and Lockwood, 2002) that provide guidelines towards measuring and assessing the importance of infrastructure facilities and developing preventive and protective plans.

The National Infrastructure Protection Plan (NIPP) "provides the unifying structure for the integration of critical infrastructure and key resources (CI/KR) protection into a single national program" (DHS, 2006). The NIPP is primarily based on a risk management framework that "establishes the processes for combining consequence, vulnerability, and threat information to produce a comprehensive, systematic, and rational assessment of national or sector risk". Risk is defined as "the expected magnitude of loss (e.g., deaths, injuries, economic damage, loss of public confidence, or government capability) due to a terrorist attack, natural disaster, or other incident, along with the likelihood of such an event occurring and causing that loss." While losses such as deaths and injuries may be directly obtained, assessing economic damage is not obvious. Further, the importance of the critical infrastructure is jointly determined by the consequences (loss), the degree of susceptibility (vulnerability), and its criticality.

The NCHRP Project 20-07, A Guide to Highway Vulnerability Assessment for Critical Asset Identification and Protection, is a study that is directly relevant to the current project. The guide outlines its objectives as: a) Assess the vulnerabilities of physical assets such as bridges, tunnels, roadways, and inspection and traffic operation facilities, among others; b) Develop possible countermeasures to deter, detect, and delay the consequences of terrorist threats to such assets; c) Estimate the capital and operating costs of such countermeasures; and d) Improve security operational planning for better protection against future acts of terrorism. The guide is particularly oriented towards State DOTs, enabling them to "identify and mitigate the vulnerabilities of consequences to highway transportation assets from terrorist threats or attacks." The decision framework is exhaustive in terms of factors identified and considered. However, the decision framework is limited since it is based on subjective rating and rankings of contributing factors as opposed to more reliable objective measures. The report recommends the synthesis of data from various sources including: a) Asset data from National Bridge Inventory System and Hazardous Materials

Information System, b) Threat data from Law Enforcement Agency, State's Emergency Management Agency, Homeland Security Office, c) Vulnerability data, d) Consequence data, e) Countermeasures data, f) Cost data, g) Policies, plans, and procedures, h) Personnel (interviews), and i) Geographic information systems (maps, drawings). Data categories (b), and (e) through (h) are not of particular interest for the current study. Table 1 below lists the different critical transportation assets.

TABLE 1. CRITICAL TRANSPORTATION ASSETS

INFRASTRUCTURE	FACILITIES	EQUIPMENT	PERSONNEL
Arterial Roads	Chemical Storage Areas	Hazardous Materials	Contractors
Interstate Roads	Fueling Stations	Roadway Monitoring	Employees
Bridges	Headquarters Buildings	Signal & Control Systems	Vendors
Overpasses	Maintenance Stations/ Yards	Variable Messaging System	Visitors
Barriers	Material Testing Labs	Vehicles	
Roads Upon Dams	Ports of Entry	Communications Systems	
Tunnels	District/Regional Complexes		
	Rest Areas		
	Storm Water Pump Stations		
	Toll Booths		
	Traffic Operations Centers		
	Vehicle Inspection Stations		
	Weigh Stations		

Source: NCHRP Project 20-07, A Guide to Highway Vulnerability Assessment for Critical Asset Identification and Protection – Contractor's Final Report.

Having identified the critical facilities, the next step is to assign critical asset factors. These include: Ability to Provide Protection, Relative Vulnerability to Attack, Casualty Risk, Environmental Impact, Replacement Cost, Replacement/Down Time, Emergency Response Function, Government Continuity, Military Importance, Available Alternate Communication Dependency, Economic Impact, Functional Importance, and Symbolic Importance. The methodology adopted – subjective ratings of factors – lends well to including the above comprehensive list. However, factors such as Economic Impact may be more reliably assessed using quantitative modeling techniques.

In conjunction with assessing criticality, a second step identified in the report (NCHRP Project 20-07) is vulnerability assessment. This is achieved using again a subjective rating across the following three factors: Visibility and Attendance, Access to the Asset, and Site Specific Hazards. The concept of determining importance of a facility by jointly considering its criticality as well as degree of vulnerability is important and will be employed in the proposed decision support tool.

The remaining steps included in the NCHRP Project 20-07 report deals with countermeasures, recovery, and cost estimates. These issues are also dealt with in a series of publications by NCHRP (NCHRP REPORT 525 Volumes 1-12) that provide comprehensive guidelines. Countermeasures and disaster recovery are beyond the scope of the current project and are not reviewed here.

Threats can be man-made (terrorist, accidental) or nature driven (earthquake, cyclones etc.). While threats from nature and accidents are not motivated, terrorist threats are motivated and targeted. It is important to distinguish among the different sources of threat in order to quantify the degree of threat in the analysis. The quantitative threat measures could be probabilistic based on the likelihood of attack and failure. Several studies have documented detailed quantitative measures of different threat sources.

Kim et al. (2002) study the economic impact of earthquakes using a multi-regional input-output model coupled with a regional commodity flow model. They study the reduction in economic activity as a function of economic sector's resiliency and the degree of network disruption – in particular to bridges in the network. Cho et al. (2001) model economic loss due to earthquake for the Los Angeles metropolitan area. They include a transportation network model and consider its impact on economic activity through capacity losses.

Karaca (2005) measures the regional economic loss from earthquakes with emphasis on economic interdependencies arising from spatial interactions through the transportation network. The study particularly focuses on the Central United States regions though the methodology developed is applicable anywhere. The study comprehensively models "buildings, the transportation network, and the economy in an integrated manner, including the recovery period following earthquakes" and is an improvement over prior studies that ignore one or more of the above dimensions. However, the models developed in Karaca (2005) are beyond the scope of the current study since we are concerned with importance of transportation facilities only. Moreover, the limitations on data availability for detailed seismic hazard and vulnerability modeling restrict the direct application of these models. However, provisions for including these more detailed models shall be included in the decision support tool.

All the above studies consider increase in travel costs as an important measure of economic loss. However, the transportation network model is a basic system optimal model. It is well known that selfish individual behavior is best modeled using ***user equilibrium***. The proposed tool will implement user equilibrium based transportation network models.

1.2 Methodologies to Identify Important Nodes/Links in a Network

Disruptions can result from a number of different types of factors such as component failures, natural disasters (e.g., earthquake), accidents, intentional disruption (e.g., terrorism or military action), etc. At an abstract level the problem has been addressed using several different techniques including: the interdiction problem, the most value node (MVN), or the most vital edge (MVE) problem.

1.2.1 MVN/MVE Problem

Given a Graph $G = (V, E)$, the MVN/MVE problem is to find the node or edge that on its removal results in maximum deterioration of the network performance. This problem has been proved to be NP-hard even when the arcs have a length of 1 (Bar-Noy et al, 1995). A generic performance measure can be the relative drop of the performance caused by a specific damage to a network. Latora et al. (2005) propose a method to evaluate the importance of an element of the network by considering the drop in the network's performance caused by its deactivation. A generic infrastructure is characterized by a variable $O(S)$ that measures its performance. They measure the importance of the damage d by the relative drop in performance. In particular, the *critical damage* is the damage D that minimizes a function O.

Another measure of the performance of a network is the increase of the distance between the origin nodes and sink nodes in a maximum flow graph. In this case, Barton (2005) simplifies the problem through the construction of equivalence classes (partitions) on the set of all possible input graphs. The specific graph G may be transformed through simplification transformations in order to determine its equivalence class. Such simplifications may aid the more efficient determination (rather than the naive brute force approach) of a vital (not necessarily unique) edge of G. Barton (2005) does not provide an algorithm to solve the problem. However, algorithms have been developed for finding the most vital edge in a spanning tree where its removal causes greatest increase in weight of spanning tree of the remaining graph (Hong Shen, 1999).

Throughput is another important performance measure that has been studied in the past. Ratliff et al. (1975) focused on finding the n most vital links in flow networks. The n most vital links of a flow network are defined as those n arcs whose simultaneous removal from the network causes the greatest decrease in the throughput capability of the remaining system between a specified pair of nodes. These n arcs are shown to be the n largest capacity arcs in a particular "cut". An algorithm is developed based on the idea of sequentially modifying the network such that the "cuts" eventually result in a reduced network with the smallest capacity.

An application of MVN/MVE problem can be found in Grubesic and Murray (2006). They evaluate the potential impacts of losing critical infrastructure elements that are geographically linked. Specifically, they evaluate the geographic impacts of losing vital nodes in geographically linked networks (e.g., telecommunication switching centers or electrical substations) by proposing and applying a spatial optimization model integrated in a geographic information system (GIS) environment which they formulate as an integer programming problem and call it NRIP (Node Removal Impact Problem). The objective of the NRIP is to either minimize or maximize the total demand impacted by the removal of nodes, depending on the intended orientation of the analysis. Constraints specify that nodes are to be removed from the network and that arcs cannot continue to be included in the network unless the associated end nodes are maintained. In the ‘‘max’’ version of the NRIP, one is actually seeking to inflict minimum damage. In the ‘‘min’’ version of the NRIP, the goal is to inflict maximum network damage.

Qiao et al. (2007) studied the allocation of security resources (budget) to water supply networks as to minimize the network's resilience. The method integrates max-min linear programming, hydraulic simulation, and genetic algorithms for constraint generation. The objective is to find a security allocation that maximizes an attacker's marginal cost of inflicting damage through the destruction of network components. They illustrate the method on two example networks, one large and one small, and investigate its allocation effectiveness and computational characteristics.

Modarres et al. (2002) address the problem of planning to minimize earthquake damages. The city street network is abstracted and evaluated using the criterion of accessibility, which includes travel time and safety. A graph is created in which the nodes are land uses (or a group of land uses), crossroads or junctions represent the city, and the arcs are the streets. Analytic Hierarchy Process (AHP) was used to determine the priority of trips, and shortest path techniques identify the fastest routes for daily trips, and the safest ones during earthquakes. A Pareto diagram shows those streets that play an important role in satisfying both criteria. On the basis of the trip patterns obtained, the accessibility of a city was estimated. This methodology helped identify the weak points of the transportation network after an earthquake. However, it can also be used to analyze plans for the expansion of existing cities. The methodology was employed in the city of Rasht after the devastating earthquake in northern Iran in 1990.

1.2.1 Interdiction Problem

The interdiction problem is defined thus: an agent attempts to maximize flow through a capacitated network while an interdictor tries to minimize this maximum flow by interdicting (stopping flow on) network arcs using limited resources. The deterministic problem is shown to be NP-complete even when the interdiction of an arc requires exactly one unit of resource (Wood, 1993). Wood (1993) proposes flexible integer programming models to solve the deterministic interdiction problem.

The stochastic interdiction problem has been addressed by Cormican et al. (1998). They formulate and solve a stochastic version of the interdictor's problem defined thus: minimize the expected maximum flow through the network when interdiction successes are binary random variables (where an attempted interdiction of arc (i, j) is completely successful with probability p_{ij} and is completely unsuccessful with probability (1-p_{ij}). Independence of interdiction successes is assumed, and only a single interdiction may be attempted on any arc. The problem is formulated as a mixed-integer stochastic program and the solution technique is based on a sequential approximation algorithm. The idea behind the sequential approximation algorithm is to create a sequence of finer and finer partitions until the gap between lower and upper bounds is sufficiently small and we can declare the problem solved, at least approximately. They show that even when the algorithm is exponential, it does not grow too large before the gap between the bounds shrinks sufficiently to yield a high-quality solution. Successful computational results are reported on networks with over 100 nodes, 80 interdictable arcs, and 180 total arcs.

An application of the interdiction problem can be found in Church et al. (2004). They focus on the loss of service or supply facilities and not on the loss of capacity of a transport link. Two new spatial optimization models called the *r*-interdiction median problem (RIM) and the *r*-interdiction covering problem (RIC) were formulated. Both models identify for a given service/supply system, the set of facilities that, if lost, would affect service delivery the most. They define the *r*-interdiction median problem as: of the *p* different locations of supply, find the subset of *r* facilities, which when removed, yields the highest level of weighted distance. And the *r*-Interdiction Covering (RIC) problem as: of the *p* different service locations, find the subset of *r* facilities which, when removed, maximizes the resulting drop in coverage. Both problems were formulated as integer programs.

1.3 Specific Applications in Assessment of Transportation Facilities

There are several research papers and technical reports on specific applications of models to assess importance of transportation facilities. The NCHRP report 525 Volume 11 (2006) describes an analytical tool to identify and prioritize state-specific transportation choke points (TCPs) according to their potential economic impact on U.S. commerce. However, the models are simplistic and consider only the increased cost of freight movement associated with the detours, and, increased inventory costs imposed by the relative uncertainty of deliveries through the detour.

A more elaborate model is developed by Matisziw et al. (2007). They employ the *p*-Cutset Problem (PCUP), a network interdiction model, to evaluate the vulnerability of freight movements in Ohio to disruptions in the interstate system. In particular, they analyze the vulnerability of truck flows within Ohio to disruptions in the interstate system.

The above work considers only freight traffic flow. Several other work focus on both passenger and freight flow together. Ham and Lockwood (2002) identify critical assets in the Nation's highway transportation network. They define *critical assets* as "those major facilities the loss of which would significantly reduce interregional mobility over an extended period and thereby damage the national economy and defense mobility". They identify the critical assets based on the following criteria: Casualty Risk, Economic Disruption, Military Support Function, Emergency Relief Function, National Recognition, and Collateral Damage Exposure. However, the methodology adopted to identify economic loss in particular is based on the additional distance of detour ignoring congestion effects.

In contrast, Scott et al. (2006) present a system-wide approach to identifying critical links and evaluating network performance. The approach considers network flows, link capacity and network topology and is based on a measure – the Network Robustness Index (NRI) – of change in travel-time cost associated with rerouting all traffic in the system should a segment become unusable.

Often the importance of transportation infrastructure is accentuated by special scenarios. A case in point is the importance of certain links and nodes in emergency evacuation scenarios. Murray-Tuite (2003) studies the problem of identifying vulnerable transportation infrastructure under emergency evacuation. The problem is represented as a game played between an evil entity and the traffic management agency (TMA). The evil entity seeks roads with higher disruption index and the TMA routes vehicles trying to avoid the vulnerable links. Unlike transportation network evacuation models, her formulation also describes household decision making behavior in an emergency evacuation.

More recently, advanced modeling techniques based on stochastic programming and variational inequalities have been developed. These techniques are still in their infancy and have not been developed sufficiently to solve large scale real-world networks. For example, Liu and Fan (2007) develop a formulation of the network retrofit problem in stochastic programming framework. The problem goes a step further than identifying critical infrastructure; they prioritize network retrofit strategies based on the importance of facilities and available budgets. Chen et al. (2007) developed a network-based accessibility measure using a combined travel demand model for assessing vulnerability of degradable transportation networks. They formulate the combined travel demand model as a variational inequality problem. The methodology adopted in this study is more comprehensive since it considers individual responses across several dimensions of travel choice simultaneously. However, efficient computation techniques for large scale transportation networks may be unavailable.

1.4 Summary of Literature Review

From the review of the literature there appears no single comprehensive decision support methodology or tool that can identify critical transportation facilities taking into account a) objective measures of economic loss in both passenger and freight transportation, b) likelihood of threats which is in turn dependent on criticality and vulnerability of the facility, under, c) both man-made and natural disasters. In following sections we propose a tool which is an important step towards developing a comprehensive decision support system to assess importance of transportation systems.

Chapter 5 CHAPTER 2: PROPOSED METHODOLOGY: IMPACT IN TRAVEL TIME

From the literature review provided previously, there appears no single decision support or tool that can identify critical transportation facilities. As also presented previously, most of the methodologies are concentrated in basically two problems: (1) finding the most vital edge (link) or node and (2) the interdiction problem (i.e. see Table 2).

TABLE 2. DIFFERENT METHODOLOGIES USED FOR THE INTERDICTION PROBLEM (TAKEN FROM CHURCH ET AL, 2004)

Reference	Objective	Decision	Constraint	Underlying Model
Wollmer (1964)	Min network flow capacity	Complete interdiction on arcs	Cardinality	Max flow through planar networks
Wollmer (1970)	Maximize min-cost	Complete interdiction on arcs	Cardinality	Min cost flow through networks
McMasters and Mustin (1970)	Min network flow capacity	Interdiction on arc capacities by units	Budget	Max flow through planar networks
Ghare, Montgomery, and Turner (1971)	Min network flow capacity	Complete interdiction on arcs	Budget	Max flow through networks
Corley and Chang (1974)	Min network flow capacity	Complete interdiction on nodes and incident arcs	Cardinality	Max flow through networks
Ratliff, Sicilia and Lubore (1975)	Min network flow capacity	Complete interdiction on arcs	Cardinality	Mac flow through networks
Fulkerson and Harding (1977)	Max shortest source-sink path	Interdiction on arc lengths by units	Budget	Min cost flow through networks
Golden (1978)	Min interdiction costs	Interdiction on arc lengths by units	Disruption Level	Minimum cost flow through networks
Corley and Sha (1982) Ball, Golden, and Vohra (1989) Malik, Mittal, and Gutpa (1989)	Max shortest source-sink path	Complete interdiction on arcs	Cardinality	Shortest path through networks
Philips (1993)	Min network flow	Interdiction on arc	Budget	Max flow through

Reference	Objective	Decision	Constraint	Underlying Model
	capacity	capacities by units		outerplanar and planar networks
Wood (1993)	Min network flow capacity	Complete interdiction on arcs. Interdiction on arc capacities by units	Budget Cardinality	Maximum flow through general networks and multi-commodity networks.
Cormican, Morton, and Wood (1998)	Min expected max flow	Interdiction attempt on arcs	Budget	Max flow through networks
Whiteman (1999)	Min interdiction costs	Complete and partial interdiction on nodes	Disruption level	Max flow through multi-commodity networks
Israeli and Wood (2002)	Max shortest source-sink path	Complete interdiction on arcs	Budget	Shortest path through networks
Burch et al. (2003)	Min network flow capacity	Complete interdiction on arcs	Budget	Max flow through nonplanar networks
Hemmecke, Schultz, and Woodruff (2002)	Max the probability of a given disruption level	Complete interdiction on arcs	Budget	Shortest path through uncertain networks

However, under the perspective of Brown et al (2005), we can understand disruption as ***the sensitivity ƒ the degradation of infrastructure performance as well as the performance of dependent systems***. Hence, for assessing critically first it is necessary to define objectives related with the degradation of the performance we are measuring. Take for example any network, the importance of each one of the component will vary if we are interested in the capacity of the network or if we are interested how reliable the components are.

For this project we have identified a suitable performance metric which explicitly accounts for traffic congestion for evaluating criticality in transportation network: the user equilibrium travel time (see Table 3). This measure is related with the economic concept of network equilibrium.

TABLE 3. OBJECTIVES AND THE RELATED METHODOLOGY

Main objective	Methodology
Assess impact in travel time	Shortest path under equilibrium condition

We now proceed to explain the formulation and the corresponding methodology that can be used to address it.

2.1 Assessing impact in travel time

As noted in the previous section, many papers have tried to address the issue of assessing criticality in a network. However, most of these methodologies do not account for the real nature of the problem which is to accurately capture the congestion effects in the transportation network. In the static context, the congestion effects can be captured using the user equilibrium model. The methodology proposed in this section assesses the criticality by computing the congestion effects based on user equilibrium with and without the transportation link/node.

In transportation network analysis, Wardrop's first principle states that every user seeks to minimize his/her transportation costs which are typically measured by the travel time. The flow that satisfies this condition, where no traveler can improve his/her travel time by unilaterally changing route, is referred as the *user equilibrium* (UE). The problem involves the assignment of origin and destination (O-D) flows to the network links such that the travel time on all used paths for any O-D pair equals the minimum travel time between the O-D (Sheffi, 1985). The mathematical formulation is

$$
\begin{aligned}
&MinZ\{T_{ij}\} = \sum_a \int_0^{V_a} C_a(v)dv \\
&s.t. \qquad \sum_r T_{ijr} = T_{ij} \\
&\qquad\qquad T_{ijr} \geq 0 \\
&\qquad\qquad V_a = \sum_{ijr} T_{ijr}\delta_{ijr}^a
\end{aligned}
$$

where, T_{ijr} is the number of trips between the O-D pair (i,j) that uses path r, C_a is the cost of flow v using link a, V_a is the flow in link a , and δ_{ijr}^{a} is a binary variable that is equal to 1 if path r between i and j uses link a and zero otherwise.

The transportation literature has developed extensive solution approaches for estimating the equilibrium. In this project, we study the problem under the usual conditions – symmetric cost functions, single user class, inelastic demand and perfect information to all users.

The algorithm we use in our study is the convex combinations algorithm, also called the Frank-Wolfe algorithm (Frank and Wolfe, 1956).

2.1.1 Criticality Measure

To define the criticality measure we use the following notation:

- $G = (N,E)$ Original network, where N is the set of nodes and E the set of edges
- $G' = (N', E')$ Disrupted network, where N' is the set of remaining nodes and E' the set of remaining edges after the disruption.

A generic measure of criticality in a network can be defined by the change in the performance of the network after the removal or damage of one its components. Therefore, the criticality of any of its components can be expressed by

$$D(i) = \frac{\Phi_{G''}(i) - \Phi_G(i)}{\Phi_G(i)}$$

Where $\Phi_G(i)$ is the performance measure of the network without disruption and $\Phi_{G''}(i)$ is the performance measure of the network after the disruption of the component i. The key in using this expression is finding an appropriate performance measure for a transportation network.

One potential measure is the shortest path by length. Let's define a set of origins and destinations as subsets of N. If there exists a path connecting any O-D pair, the distance d_{ij} between these two nodes is positive and if there exist no path then $d_{ij} = \infty$. The shortest path length l_{ij} between nodes i and j can be defined as the smallest sum of the physical distances throughout all possible paths. Latora et al. (2005) used this measure to assess criticality. However, this measure is not suitable to address effect of congestion in user decision making.

For a transportation network, an appropriate measure is the travel time under UE conditions. Under UE conditions, each user's choice is in response to the congestion levels on the network. The travel times obtained at each link captures the underlying behavior of the users in the network. Therefore, we use the aggregated value of travel time over all users as a measure of performance.

The measure is given as the summation of all arc travel times (t) or equivalently we can use the objective function of the equivalent optimization problem: $\Phi_G = \sum_{\forall a} \int_0^{x_a} t_a(\omega)d\omega$ where x is the flow at link a. If there is at least one path connecting any O-D pair this value is a positive number but if there is not a path the travel time will became infinite. Hence, we also assume that there is typically path choice between any two given O-D pairs. This measure of criticality differs from Nagurney and Qiang (2008) definition. They developed a measure that is an average network efficiency matrix that does not count a pair that has no associated demand. In our measure we do not weight our disutility measure by the demands. That is that even if an origin or destination node is disrupted, we do not eliminate the demand associated with it.

Moreover, our performance measure can be extended to address elastic demands. In the elastic case, the trip rate between the O-D pairs is not necessarily deterministic but will be influenced by the level of service in the network (See Sheffi, 1985). Then the performance measure can be rewritten as

$$\Phi_G = \sum_{\forall a} \int_0^{x_a} t_a(\omega) d\omega + \sum_{rs} \int_0^{q_{rs}} D_{rs}^{-1}(\omega) d\omega$$

Where q_{rs} is the trip rate between an O-D pair *r-s* which is function of the travel time between *r* and *s*. $D_{rs}^{-1}(.)$ is the inverse of the demand function associated with O-D pair *r-s* and x_a is the flow at link *a*.

In summary the ratio $D(i)$ requires the computation of the impact of the disruption of the link in the travel time under user equilibrium conditions. Given the nature of the problem, the most appropriate performance measure Φ is the summation of travel times under user equilibrium or more clearly the total travel times after the traffic assignment without the disruption $\Phi_{G''}$ and with the disruption Φ_G . Observe that this ratio captures:

- The behavior of the users in the network, ie.: given that the disruption drivers can change their routes.
- The effects over other links, i.e.: other links are impacted by the disruption because drivers change their routes and this affects the related links in terms of their new travel times.

2.1.2 Algorithm to Assess the Criticality of a Link

As mentioned previously the idea is to assess the equilibrium travel time changes due to disruption of a single link. The approach uses the Frank-Wolfe algorithm (see subsection A) to the estimate the travel times and can be summarized in the following steps:

- Step 1: Choose one link and eliminate or reduce its capacity.
- Step 2: Use Frank-Wolfe algorithm and estimate travel time (*UE*)
- Step 3: Store the travel time and select another link. Repeat steps 1 to 3 until all links have been evaluated.
- Step 4: Compare with the travel time under *UE* without disruptions and rank from more critical to less critical based on which links affects the most the travel time.

The algorithm pseudocode is explained in Figure 1 and Figure 2 using these additional definitions:

- *G* = (*N*,*E*) Original network, where *N* is the set of nodes and *E* the set of edges
- *G'*= (*N'*, *E'*) Disrupted network, where *N'* is the set of remaining nodes and *E'* the set of remaining edges
- *N** = *N*-N' Set of nodes to be deleted (disrupted)
- *E** = *E*-*E'* Set of edges to be deleted (disrupted)

- DUE* User Equilibrium for *G*

Main (Ranking of nodes and links, given G, N*, E*)

```
Initialize T ← 0
For all n* ∈ N*
E*← Find entering/exiting links to/from n*
E ← capacity of e* ≈ 0
For all n ∈ N
T ← Compute DUE(G)
For all e* ∈ E*
E ← capacity of e* ≈ 0
For all e ∈ E
T ← Compute DUE(G)
Ranking(T)
```

FIGURE 1. MAIN ALGORITHM

Ranking (given T, DUE*)

```
For all (n* ∈ N*) U (e* ∈ E*)
R ← (DUE*-T)/DUE*
Sort(R)
```

FIGURE 2. RANKING SUBROUTINE

The algorithm has been implemented using TransCAD's GISDK and the details of this implementation is presented in Section 3.

A. FRANK-WOLFE ALGORITHM

The algorithm was originally used as a procedure for solving quadratic programming problems with linear constraints. At each step the objective function is linearized and then a step is taken in a direction that reduces the objective (minimization problem) while maintaining feasibility. It is the most common algorithm for determining the equilibrium flows in transportation networks and the procedure is, as described by Ortúzar et al (2006), as follows:

- Step 1: Select a suitable (feasible) initial set of current links costs, usually free-flow travel times (cost = 0), and initialize flows $V_a^0 = 0$ and the counter n.
- Step 2: Build the set of minimum cost trees with the current costs and update counter ($n = n + 1$).
- Step 3: Load the complete set of the trips matrix of these trees using all or nothing (sending all the flow), obtaining a set of auxiliary flows, F_a.
- Step 4: Calculate the current flows as $V_a^n = (1 + \varphi)\ V_a^{n-1} + \varphi F_a$, where φ is such a value the minimizes the objective function.

- Step 5: Calculate a new set of current link costs based on V_a^n; if the flows have not changed substantially in two consecutive iterations, stop; otherwise go to step 2 and repeat the process.

Chapter 6 CHAPTER 3: Framework

In this section we provide a description of the architecture of the project. The environment under which this project has been developed is TransCAD using TransCAD's program language, Geographic Information System Developers Kit (GISDK). Before going into the details of the code we first explain briefly the functionalities and logic under TransCAD's environment.

3.1 TransCAD

TranCAD combines a Geographic Information System (GIS) and transportation modeling capabilities in a single integrated platform that provides:

- A powerful GIS engine with special extensions for transportation
- Mapping, visualization, and analysis tools designed for transportation applications
- Application modules for routing, travel demand forecasting, public transit, logistics, site location, and territory management
- Add-ins are macros or dialog boxes that are launched within TransCAD. One can create from simple to sophisticated add-ins using the GISDK to provide users access to existing software functions; to add new capabilities to the GIS engine; or to create links to one's own applications. The simplest add-ins are macros that run when they are selected by the user. The most flexible and powerful add-ins are custom toolboxes that provide users with push-button access to tools that you have programmed. These toolboxes look like the standard toolboxes used in all Windows applications. It is the latter that we have developed for this project.

TransCAD works using some specific GIS files which are called **layers**, all the layers are stored under one **database** (the extension is .dbf), the database and map layer (which displays the map) are contained in a **Worksheet file.** In order to run a procedure or a subroutine with the traffic assignment two more files are needed. One is the **network file** which is created using fields of the line layer and the second one is the **OD matrix file** which can be either imported from, for example an Excel file, or built using TransCAD features.

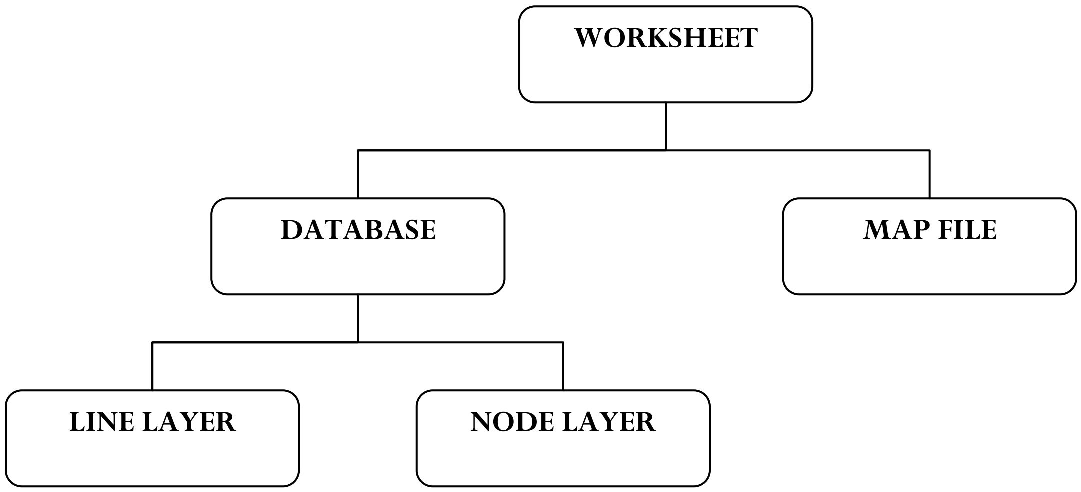


FIGURE 3. TRANSCAD SCHEME

3.2 Procedures

As mentioned in Section 2.1 we have developed a customized toolbox that provides users with push-button access to the tools we have programmed. The tools are three and the instructions of how to install and use these tools are presented in Section 3. The toolbox is nothing but a dialog box that contains 3 macros: Database Preparation, Base Case Traffic Assignment and Network Assessment.

3.2.1 Dialog Box

The dialog box groups the three main macros creating a toolbox menu with buttons that activate each macro. More clearly:

- Line 1: Creates the toolbox “UTRC”.
- Lines 2-4: Create a button with the name “Database Update” that runs the macro “Database Preparation with the command **RunMacro(“Name of the macro”)**.
- Lines 6-7 and 8-10 are the same as Lines 1-2.
- Lines 11-14: These sentences are reserved for each dialog box.

```
1       DBox “UTRC" ,,32 toolbox
2       Button "Database Update" 4,.5,24 do
3           RunMacro("Database Preparation")
```

```
    endItem
    Button "Base Case" 4,2.25,24 do
        RunMacro("Base Case")
    endItem
    Button "Cases" 4,4,24 do
        RunMacro("Network Assessment")
    endItem
   close do
   Return()
   endItem
   enddbox
```

FIGURE 4. DIALOG BOX

3.2.2 Database Preparation

As mentioned in Section 2.1 TransCAD works with a Database that contains different layers. For running the procedures used in this report and included in the Toolbox two are the most important layers the **Highway Layer** and the **Node Layer**. Other layers can be added to visualize the network, for example the Water Layer and a County Layer.

- Highway Layer

  This is the most important layer because it contains the links and it is connected with the node layer. The Highway Layer can be constructed starting from the default Highway Layer provided by TransCAD. Some fields are necessary to be added in order to use the Toolbox (see Table 4).

TABLE 4. BASIC FIELDS NEEDED IN THE HIGHWAY LAYER

Field	Description	Source
ID	Link Identification field	TransCAD default
Distance (in miles and km)	Length of the link	TransCAD default
Number of Lanes	Number of lanes per link	TransCAD default
Capacity	Capacity of each link per lane	Need to be created
Free Flow Speed	Free Flow Speed per each link	Need to be created

Field	Description	Source
Alpha	Alpha parameter for the BPR function	Need to be created
Beta	Beta parameter for the BPR function	Need to be created

As noted in Table 4 just the last three fields need to be created. Other fields come by default with the Highway Layer of TransCAD. Some other fields can be added or kept in the Highway Layer such as the Type of Route Field and the Name of the link field. For this project we have used the NYDOT BPM's highway layer developed also under TransCAD (see Appendix for details).

- Node Layer

  The Nodel layer comes by default whenever one selects the Highway layer from TransCAD. The most important fields are the **ID** field for the node and the **Longitude** and **Latitude** fields.

The first macro contained in the Toolbox contains the macro that prepares the database to run the algorithm since it is necessary to have some temporal fields to store temporarily some values and to create the field that will contain the results. The general steps are details as follows.

General Steps

1. Obtain the structure of the table.
2. Create a temporal field to store the capacity of the selected links.
3. Create the field where we store the ratio that indicates the criticality.
4. Obtain the IDs of the selected links
5. Using the selected links copy all the capacity values in a temporary field and copy them into a txt file.
6. For all the selected links, copy the values of the Capacity field of the Highway layer into the temporary field of the Highway layer.

To clarify some of the sentences and functions we included an Appendix section that has code details and comments. It is important to read that section before doing any modification in the code.

3.2.3 Base Case

The second macro contains the base case traffic assignment. In this macro we use the network without disruptions in order to obtain the measure that works as the basis for comparison and to compute the criticality ratio.

General Steps

0. General information

   Database name: ie.: HN050131.DBD

   Line Layer: ie.: Highway

   Node Layer: ie.: Highway Node

   OD Matrix: ie.: highway_am.mtx[1]

   Network: ie.: SP.net

   Output: ie.: ASN_LinkFlow2.bin

1. Using the database, specifically the line layer and the node layer, construct the network file.

2. Use the TransCAD procedure to run the traffic assignment.

3.2.4 Network Assessment

The last macro runs the same procedure created before iteratively for all the links selected.

General Steps

0. General information

   Database name: ie.: HN050131.DBD

   Line Layer: ie.: Highway

   Node Layer: ie.: Highway Node

   OD Matrix: ie.: highway_am.mtx

   Network: ie.: SP.net

   Output: ie.: ASN_LinkFlow2.bin

1. Open the output file of the base case and obtain the TOTAL IN VEHICLE travel time and store in the variable sum1.

2. For all selected links:

   2.1. Change the capacity of the current link to 1 or a very low number.

   2.2. Build the network with the **Network Building operation**.

   2.3. Run the procedure **Traffic Assignment**.

[1] The highway_am.mtx is a matrix file that contains different OD matrices under the same file. Each OD matrix is identified depending on the type of trip such as Trucks, Drivers Alone, etc. For the example we present in this report we used the QuickSum option which is the aggregation of all type of trips.

2.4. Restore the capacity of the link

2.5. Open the output file of the base case and obtain the TOTAL IN VEHICLE travel time and store in the variable sum.

2.6. Compute the ratio using Section's 1 criticality measure.

2.7. Find the position of the selected link and store the current value of the ratio variable in its corresponding field.

Chapter 7 CHAPTER 4: Instructions

4.1 Installing the Add-in

Before installing:

- Create the folder: **0_Base under the following path:** “**c:\\Program files\\TransCAD\\0_Base**”.
- Copy all the files provided in the CD zipped folder called: **0_Base.zip**.
- To work with the Manhattan network open the file Manhattan_1.wrk

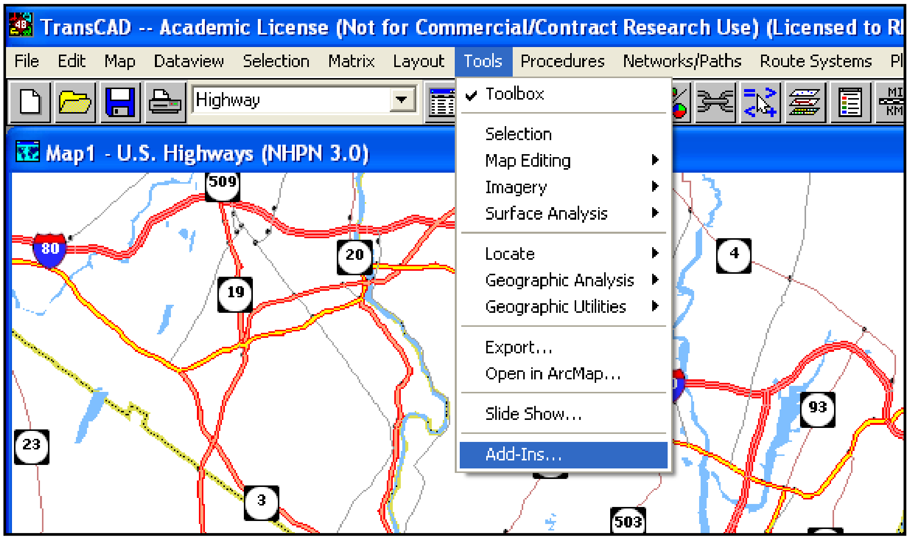
1. Compiling the macro

a. If you are using a different data or if you want to modify the provided network (i.e.: different network name, different OD matrix, etc.) you first need to modify the txt code (Main.txt) with the corresponding paths for the layers and the fields used in the procedures (see Section 4.3). Once the file has been modified, save the file as a GISDK Code.

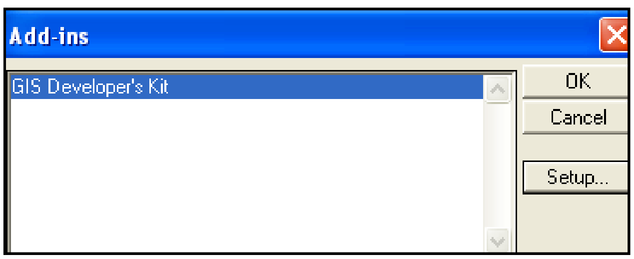
> Important:
>
> Do not forget to save your GISDK code with the extension **“rsc”**
>
> - Choose **File / Save as**
> - In the option **Save as type** choose **All files**
> - Write the name with the extension **rsc** (eg. Name.rsc)

If you are using the macro without modifications, then go directly to (1.b).

b. Go to the menu **Tools** and choose option **Add-Ins…** and wait for the Add-In window to pop up.

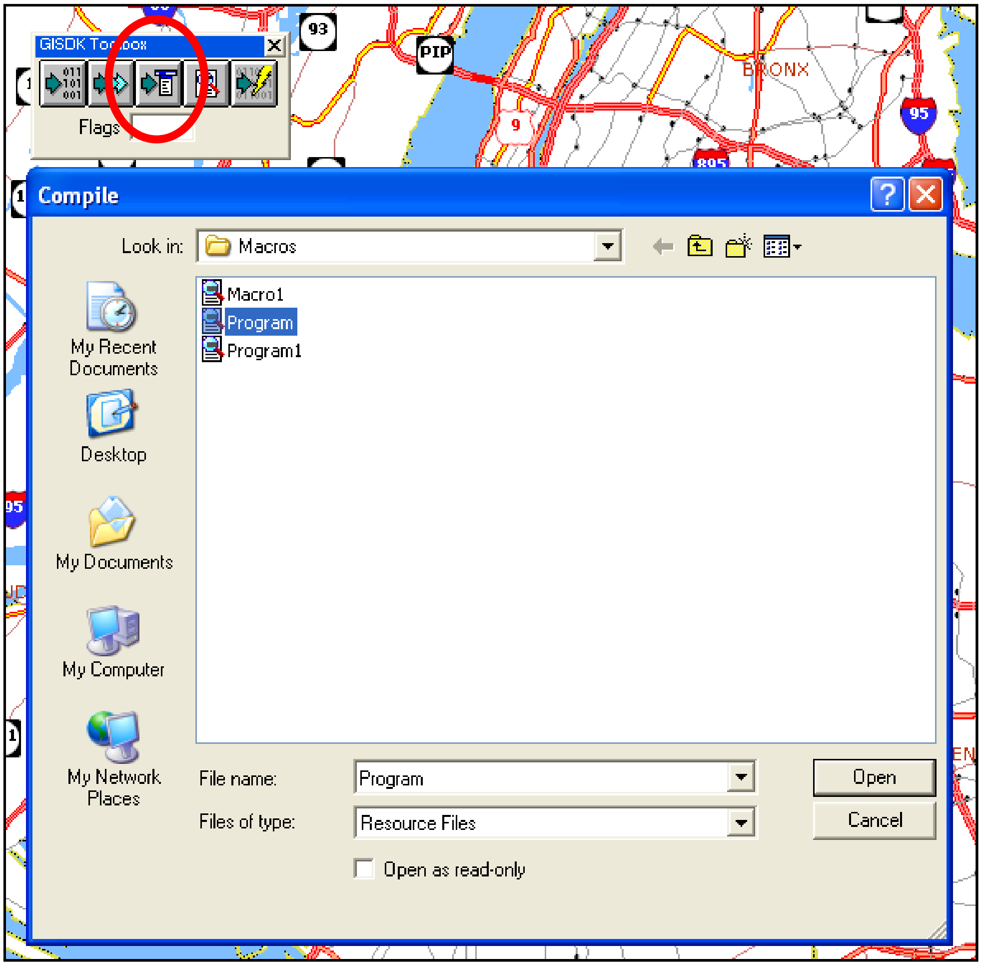


c. In the Add-ins window check that the **GIS Developer's Kit** is selected and press **OK** and wait for the **GISDK Toolbox** to pop up.

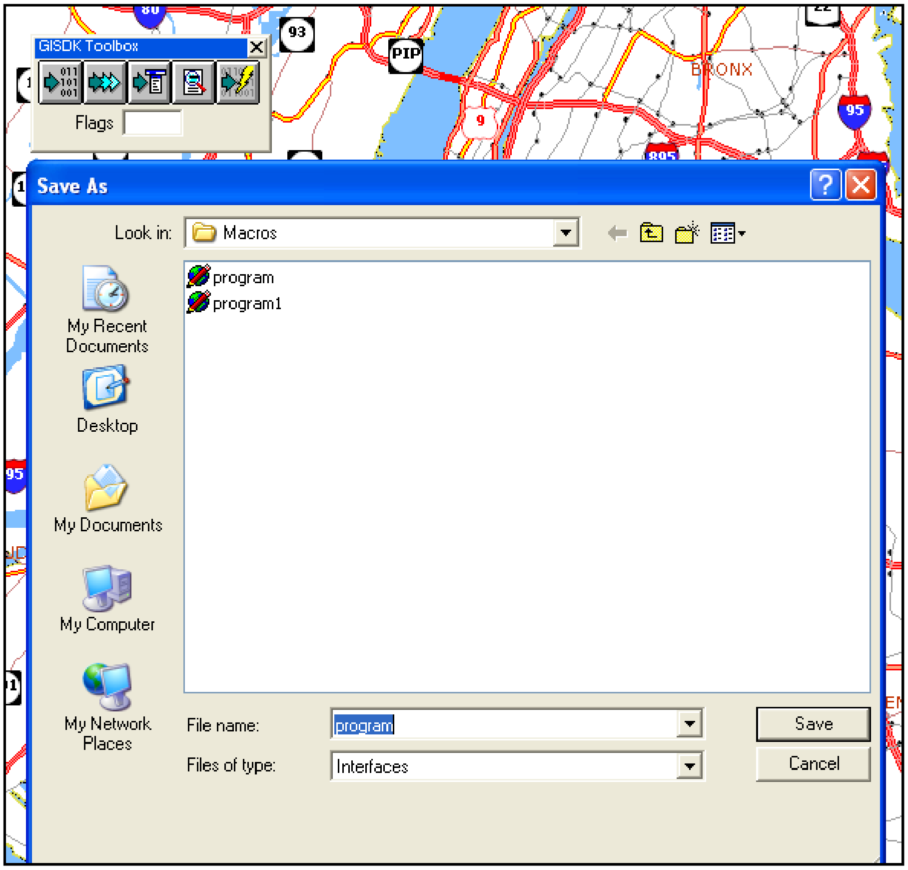


d. The **GISDK Toolbar** contains 5 buttons; the third button compiles the **GISDK** (**Compile to UI**).

- Choose this option (see the red circle in the following figure). This displays the the **Compile** window. Now choose the macro you want to compile. In the example we chooose Program. If you are using the **0_Base** file provided with the CD, then go to **0_Base/Macros** and choose **mainprog.rsc**.



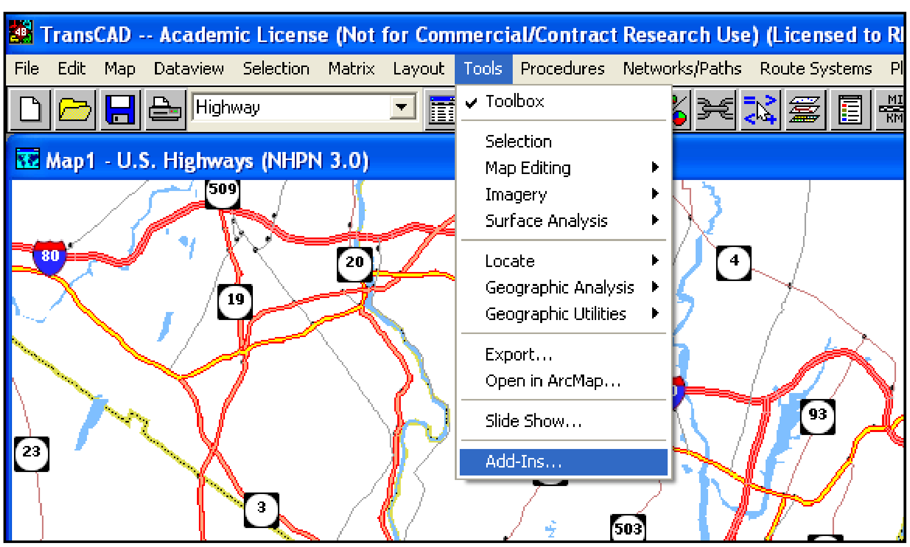
- This will immediately pop up another window that saves the Macro. Save the macro with the same name of the rsc file you have opened.



- If your macro does not contain errors you should receive a message saying **Compilation successful**.

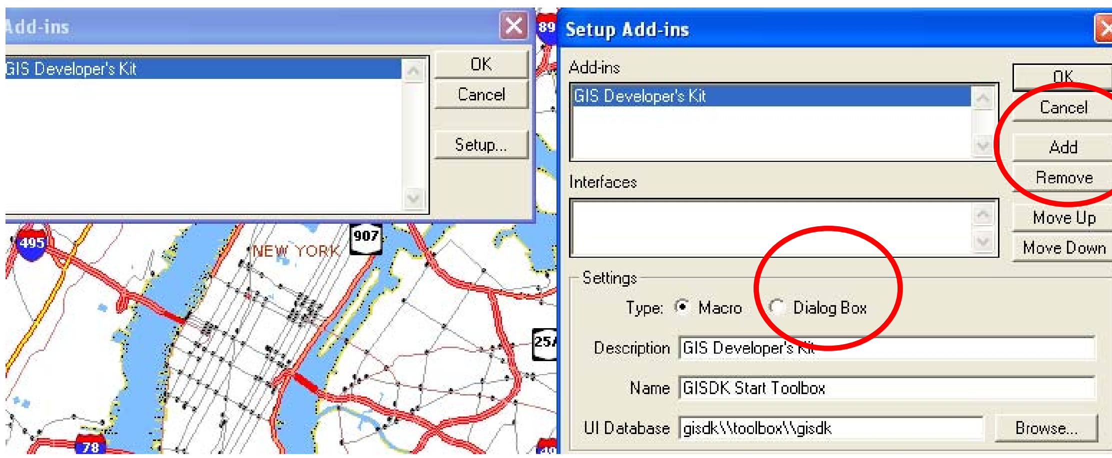
2. Adding the macro as an Add-in

a. Go to the menu **Tools** and choose option **Add-Ins…** and wait for the Add-In window to pop up.

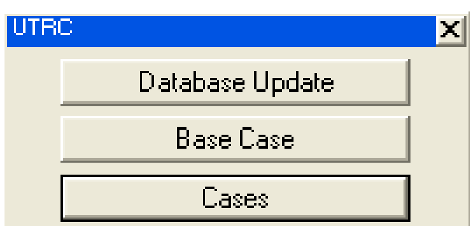


b. In the Add-ins window check that the **GIS Developer's Kit** is selected and press **Setup…** and wait for the **GISDK Toolbox** to pop up.

c. In the **Setup Add-ins** window press the button **Add** and check the option **Dialog Box** (see the circles in the figure). Now in **Description** put the name, eg. UTRC and in the field **Name** put the same name that you use in the original txt file for the Dialog Box, for our example it is UTRC. Now you browse the macro file, choose the one you have already created in Step 2.



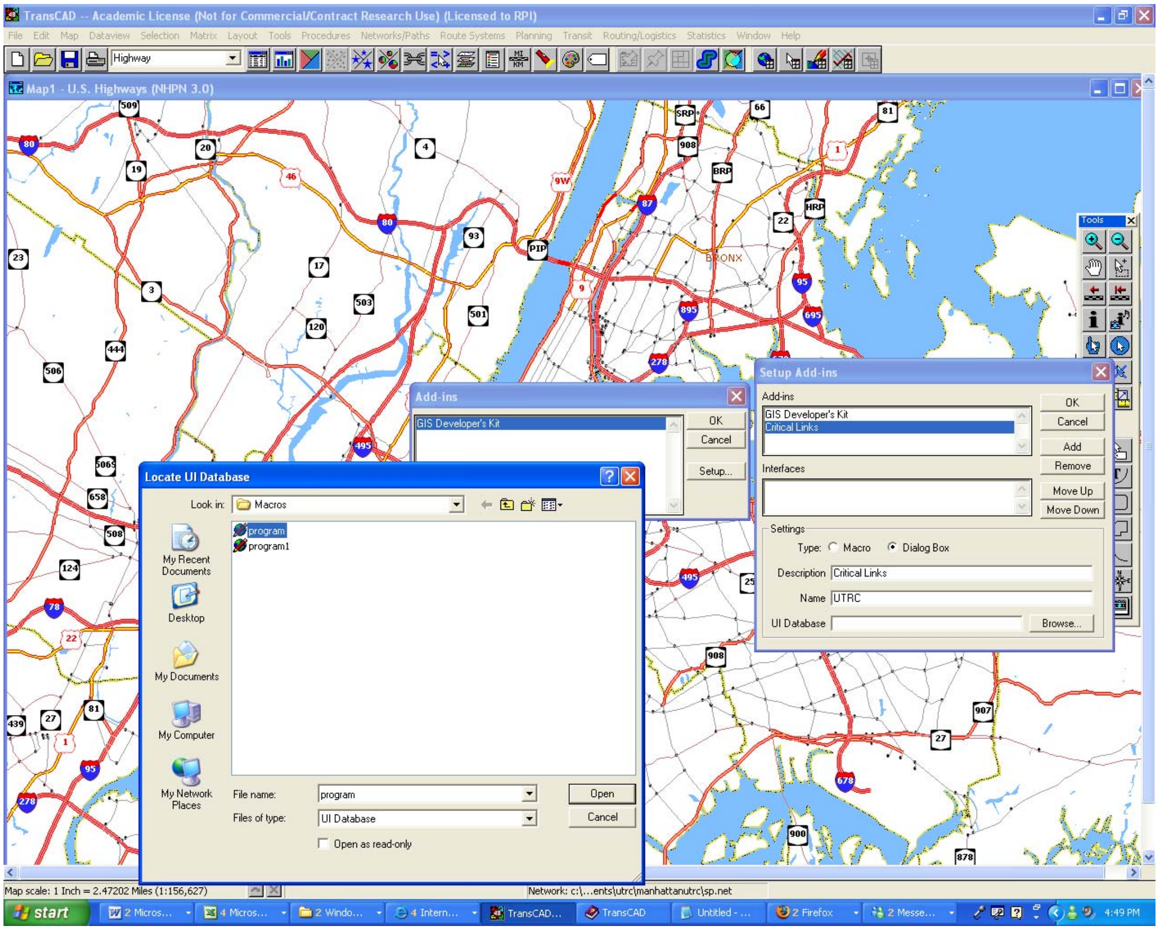
d. The following menu bar must pop up. Note that the name of the bar is the same that you wrote in the Name's field.



The program consists in three macros embedded in a Dialog Box. The functions of these buttons are

- **First Button: Database Preparation**: This step prepares the database adding the fields Temp and Ratio (see XX).
- **Second Button: Base Case:** This button calls the macro that runs the base case traffic assignment.

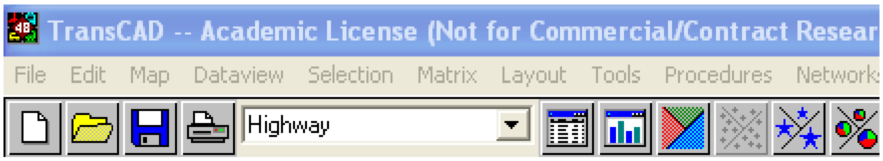
- **Third Button: Network Assessment:** This button calls the macro that runs the traffic assignment for all the selected links.



4.2. Running the Program

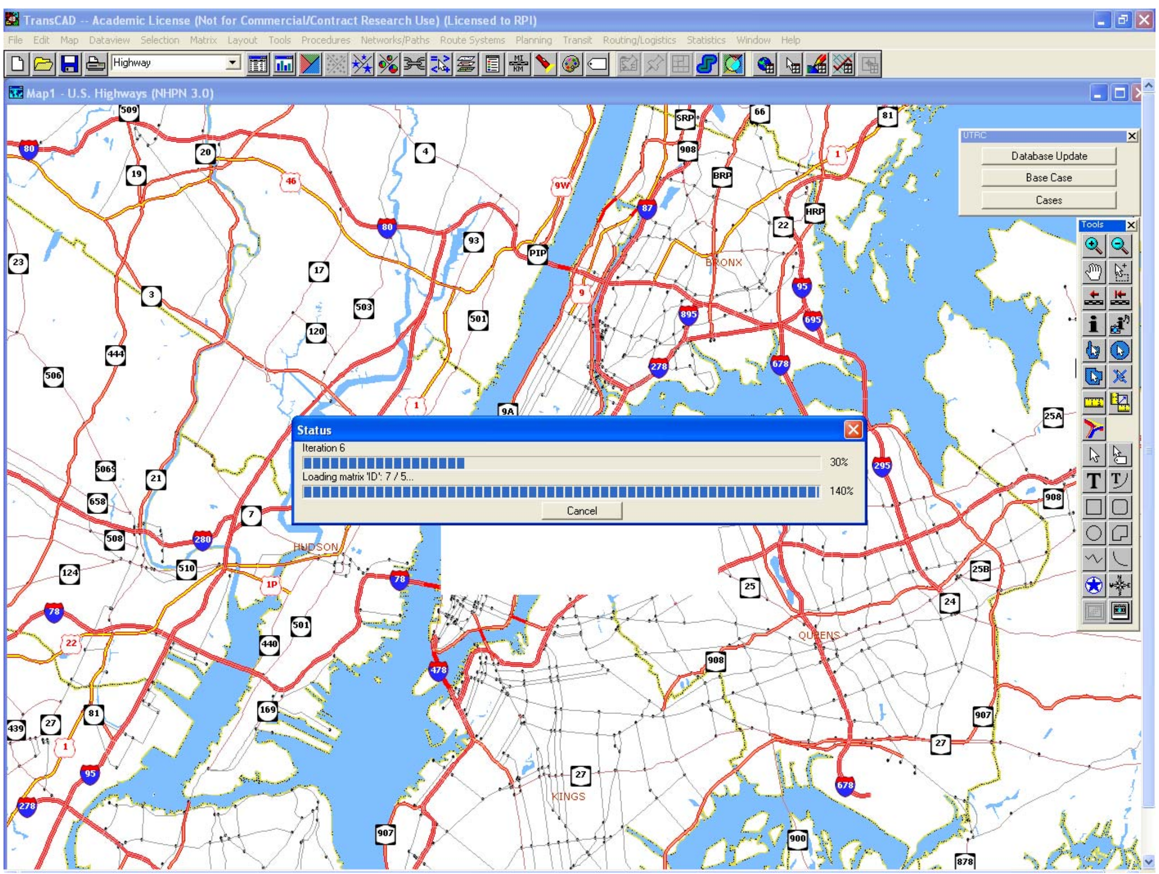
To run the program the steps are as follows:

1. Open the worksheet and assure that:
    a. The worksheet contains a highway and node Layer
    b. The Highway layer as active

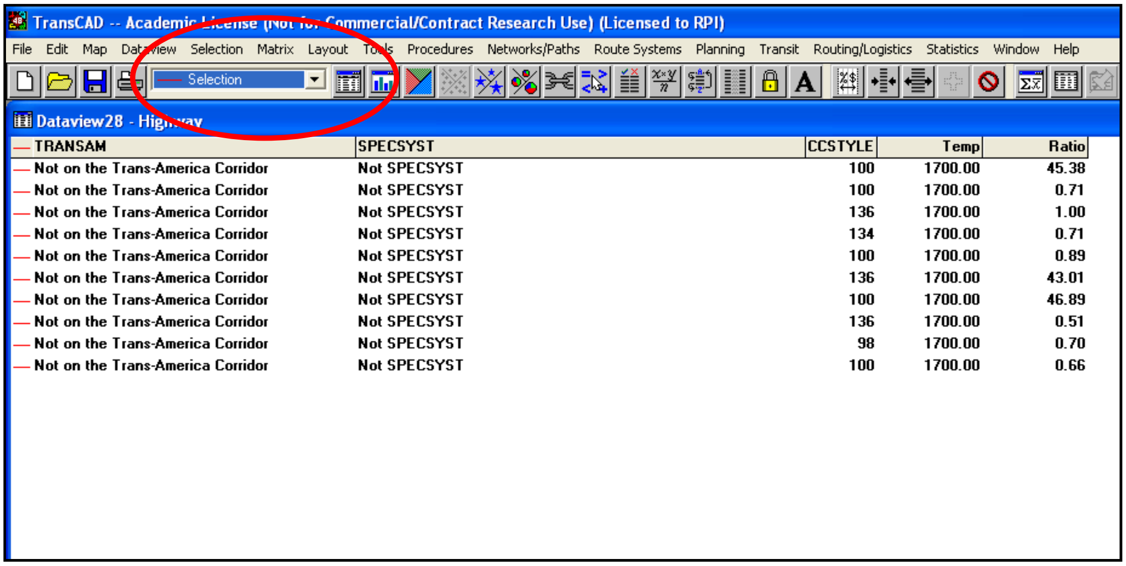


    c. The OD matrix file is open

2. Select the links you want to evaluate using Transcad's selection options.
3. In the new Menu press the button Database Preparation.
4. Press the button Base Case.
5. Press the button Net. Assessment.

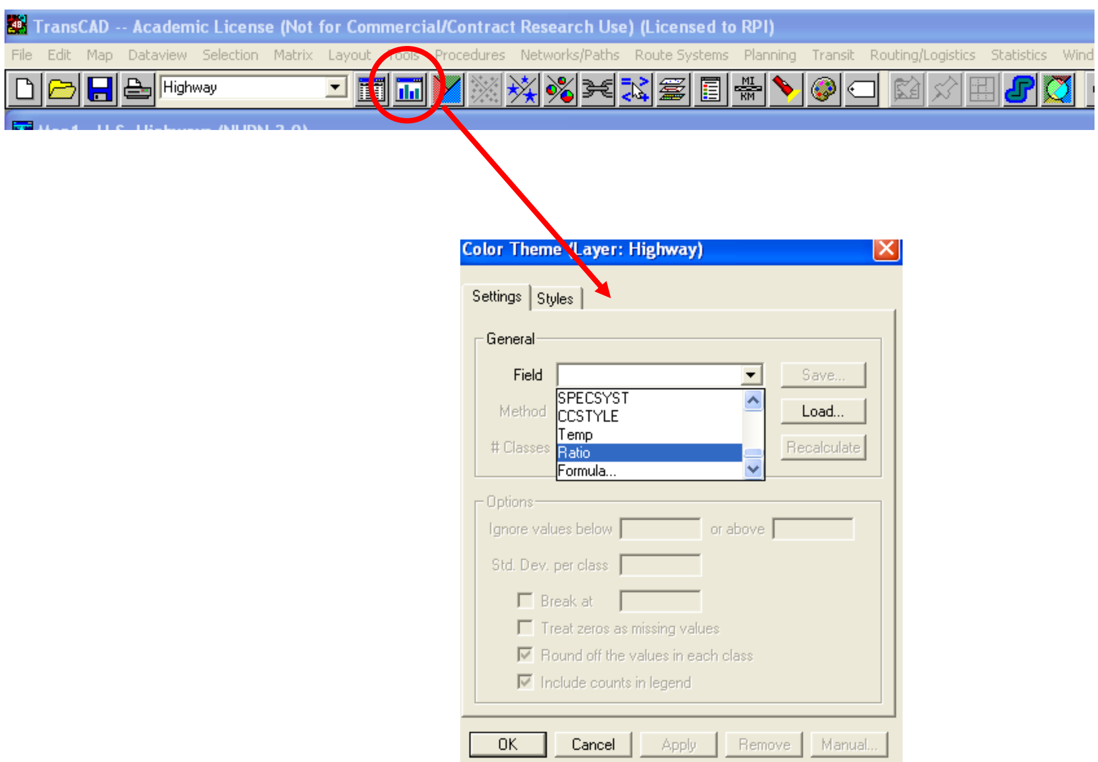


6. The results can be accessed opening the Highway dataview (see circle in the following figure) and choosing the option to show only the selected links.



TRANSAM	SPECSYST	CCSTYLE	Temp	Ratio
Not on the Trans-America Corridor	Not SPECSYST	100	1700.00	45.38
Not on the Trans-America Corridor	Not SPECSYST	100	1700.00	0.71
Not on the Trans-America Corridor	Not SPECSYST	136	1700.00	1.00
Not on the Trans-America Corridor	Not SPECSYST	134	1700.00	0.71
Not on the Trans-America Corridor	Not SPECSYST	100	1700.00	0.89
Not on the Trans-America Corridor	Not SPECSYST	136	1700.00	43.01
Not on the Trans-America Corridor	Not SPECSYST	100	1700.00	46.89
Not on the Trans-America Corridor	Not SPECSYST	136	1700.00	0.51
Not on the Trans-America Corridor	Not SPECSYST	98	1700.00	0.70
Not on the Trans-America Corridor	Not SPECSYST	100	1700.00	0.66

7. To change the colors of the links using the Ratio field you need to use the **Color Them Map Wizard** (see button inside circle in the figure). This button opens a window where you can select the Ratio field and choose the colors and style you want use to present them.



4.3 Modifying the GISDK Code

Before modifying the GISDK code we recommend the reader to carefully follow the Appendix in order to understand the details of the code since the GISDK code is not as flexible as a traditional programming language such as C, C++ or Visual Basic. To run a different network there are several updates to be done in the GISDK code. Once you have updated the GISDK compile it again following the procedure 3.1.

The updates to be done are listed below:

- Files Path update:

  The path for all the files used in this program is "**c:\\Program files\\TransCAD\\0_Base**".

  We recommend creating this directory and copying all the files there.

- Database update:

  The database file is called during the network building procedure and the traffic assignment procedure. To change the database you need to go to the Base Case Macro and the Network Assessment Macro and modify the paths:

  - **Opts.Input.Database = "C:\\Program Files\\TransCAD\\0_Base\\DATABSE_NAME.DBD"**
  - **Opts.Input.[Link Set] = {"C:\\Program Files\\TransCAD\\0_Base\\DATABSE_NAME.DBD|Highway", "Highway"}**

- Highway Layer and Node Layer update:

  The Highway and node layer are called during the network build and traffic assignment procedures, we recommend changing the name of the line and node layers to Highway and Highway Node respectively. This can be done by changing the layer name in the Layer option in TransCAD.

- OD Matrix update:

  The OD Matrix is called in the Traffic Assignment procedure, to update you need to change the OD Matrix file name in

  Opts.Input.[OD Matrix Currency] = {"C:\\Program Files\\TransCAD\\0_Base\\OD_MATRIX_NAME.mtx", "QuickSum", "Rows", "Columns"}

- Network Building update

  The network building step requires the change in all the fields of the database used to construct the network:

  Opts.Global.[Link Options] = {{"Length", "Highway.Length", "Highway.Length"}, {"ID", "Highway.ID", "Highway.ID"}, {"Length", "Highway.Length", "Highway.Length"}, {"Dir", "Highway.Dir", "Highway.Dir"}, {"[ID:1]", "Highway.[ID:1]", "Highway.[ID:1]"}, {"TOT_LANE", "Highway.TOT_LANE", "Highway.TOT_LANE"}, {"Alpha", "Highway.Alpha", "Highway.Alpha"}, {"Beta", "Highway.Beta", "Highway.Beta"}, {"Capacity", "Highway.Capacity", "Highway.Capacity"}, {"FF", "Highway.FF", "Highway.FF"}}

The network is store in the file with .net extension:

Opts.Output.[Network File] = "C:\\Program Files\\TransCAD\\0_Base\\NETWORK _FILE_NAME.net"

To update the network file the user just need to change the name of the network file but the user must remember that this file is an input for the traffic assignment step.

- Traffic Assignment update

  The traffic assignment procedure requires updating the network file, the OD Matrix file and the free flow, capacity, alpha, beta fields (their names should be the same as in the database file). It also requires to choose a convergence rate and the maximum number of iterations:

Opts.Input.Network = "C:\\Program Files\\TransCAD\\0_Base\\SP.net"

Opts.Input.[OD Matrix Currency] = {"C:\\Program Files\\TransCAD\\0_Base\\highway_am.mtx", "QuickSum", "Rows", "Columns"}

Opts.Field.[FF Time] = "FF"

Opts.Field.Capacity = "Capacity"

Opts.Field.Alpha = "Alpha"

Opts.Field.Beta = "Beta"

Opts.Field.Preload = "None"

Opts.Global.Convergence = 0.1

Opts.Global.Iterations = 30

The traffic assignment procedure requires one to choose a file where the traffic assignment flow and time resulting from the traffic assignment:

Opts.Output.[Flow Table] = "C:\\ProgramFiles\\TransCAD\\0_Base\\TRAFF_ASSIGNM.bin"

We recommend the user to keep the name that we provided in the program "ASN_LinkFlow2.bin" since this name is referred later in some other steps of the program.

Chapter 8 CHAPTER 5: Implementation: Manhattan Network Case Study

5.1 Network Description

For this test we evaluated the importance of the main access infrastructures to Manhattan Island. The network consists in the four main zones that compose NY City: Bronx, Queens, Brooklyn, and Manhattan. We have also included all New Jersey counties (see Figure 5). The infrastructures considered are the bridges, tunnels and highways presented in **Error! Reference source not found.**. Note that these facilities include sections with different directions (to Manhattan or off Manhattan).

FIGURE 5. NEW YORK CITY

TABLE 5. FACILITIES UNDER ANALYSIS

Zone	Facility
New Jersey - Manhattan	
	Lincoln tunnel
	Holland tunnel
	Washington Bridge
Bronx – Manhattan	
	Cross Bronx Expy
	Macombs Dam Bridge
Queens – Manhattan	
	Queens Midtown tunnel
Brooklyn - Manhattan	
	Brooklyn Battery Tunnel
	Brooklyn Bridge
	Manhattan Bridge
	Williamsburg

The network has been developed in TransCAD using the network included in the New York DOT's Best Practice Model (BPM). To perform the Traffic Assignment, TransCAD requires an O-D matrix, a network with the appropriate attribute fields, and the line layer from which the network was derived. In addition, there are optional inputs, such as:

- Linkname: Name of the link type
- Code: A code for the link type category

- Alpha: The α parameter in the BPR function
- Beta: The β parameter in the BPR function
- Speed: The default link speed in miles per hour for the link type
- CAP: The capacity per lane in vehicles per hour
- LANES: The number of lanes
- ERROR: The percentage error term for SUE

These inputs have to be part of the line layer. The default line layer built from TransCAD GIS Highway layer includes some of the parameters. However some of them are not included by default. Hence, they were added to the line layer. The additional parameters were:

1. **Free Flow Speed:** 65 mph in Highways and Freeways and 25 in Streets and Roads.
2. **Capacity:** 1700 per lane
3. **Alpha:** 0.1
4. **Beta:** 4

The OD matrix considers the 4,000 zones of the NYDOT's BPM for the total AM Peak trips for the year 2002. The OD matrix table cannot be shown in this report but it is included in the CD under the file name **highway_am.mtx**. The files used are included in the CD and contain the following files:

TABLE 6. FILES USED FOR THE MANHATTAN NETWORK

File	**File Name**	**Description**
Worksheet:	Manhattan_1.wrk	This file contains the Transcad worksheet which collects all the files used to run the traffic assignment.
- Map	US	
- Database	HN050131.dbd	Contains the layers: Highway and Highway Node
- Network	SP.mtx	Network matrix
- OD matrix	highway_am.mtx	
Macros:		

File	File Name	Description
- GISDK code	mainprog.rsc	GISDK code
- Add-in code	Mainprog	

5.2 Results and Analysis

In this part we will discuss the results of the Manhattan test network. We measure the criticality as an increase in vehicle hour time with the following considerations:

1. We have tested the program evaluating the facilities from Table 1 only. The default TransCAD highway line layer, has the facilities divided in Sections (east bound/west bound for example). We have kept this structure since aggregating or grouping can affect some other parameters of the line layer (such as speed or number of lanes). The facilities and their sections as used in the line layer are
    - Lincoln Tunnel (2 sections): To Manhattan and to N. Jersey.
    - Holand Tunnel (2 sections): East Bound (to Manhattan) and West Bound (to N. Jersey).
    - Queensboro Bridge (2 sections): To Manhattan and to Queens.
    - G. WashingtonBridge (8 sections): 4 sections to Manhattan and 4 to N. Jersey.
    - Williamsburg Bridge (2 sections): East Bound (to Brooklyn) and West Bound (to Manhattan).
    - Queens Midtown Tunnel (2 sections) East Bound (to Queens) and West Bound (to Manhattan).
    - Brooklyn Battery Tunnel (1 section): Both directions.
    - Brooklyn Bridge (2 sections): East Bound (to Brooklyn) and West Bound (to Manhattan)
    - Croxx Bronx Exp. Bridge (2 sections): East Bound and West Bound
    - Manhattan Bridge (1 section): Both directions.
    - Macombs Dam Bridge (1 section): Both directions Manhattan – Bronx.
2. The results presented include the final ratio VHT/VTH_0 where VHT is the total vehicle hours under each scenario.
3. Each scenario is constructed by reducing capacity of each link up to the minimum possible in this case the capacity of each lane was reduced to 1.
4. Note that these results depend on the original OD matrix.

For each traffic assignment, we have used 30 iterations for an average convergence rate of 3% which run, in average, 36 minutes.

Under these considerations we have found that the three facilities that connect New Jersey and Manhattan are the most important. The facilities that are ranked as more important are ones that takes the traffic in and out of Manhattan. In the rankings of the top 10 facilities, only 2 of them carry flow out of Manhattan (Queensboro Bridge and Lincoln tunnel). This is expected since we have used the AM Peak OD Matrix and Manhattan is big attractor of trips. This proves that our criticality measure is consistent with the real pattern of trips and the changes that could possibly occur due to route behavior. The Lincoln Tunnel and the Holland tunnels section in direction to Manhattan are ranked as the most important links with criticality measures of 52.63% and 39.73% respectively.

An interesting result is that G. Washington Bridge is ranked 5th. This is due to of the structure of the built-in line layer. By dividing the George Washington Bridge in 8 sections, only one section can be disrupted at a time so the flow using the George Washington Bridge can be split into the remaining sections. Further research can be done in assessing the criticality of all sections of the G. Washington Bridge, but for this report we are assessing each section independently[2].

Another interesting result is that the facilities connecting New Jersey and Manhattan are in general ranked higher than the ones connecting Brooklyn or Queens to Manhattan. Given that we are using a 4,000 zones OD Matrix that covers the entire region under study (Manhattan, Bronx, Queens and New Jersey) we can infer that this is due to

- That drivers in Brooklyn, Queen and Bronx are not highly affected since they have alternative modes of transportation to travel to Manhattan or they do not require to pass through Manhattan to reach their destinations

- That driver in New Jersey either have Manhattan as their final destination or they need to pass through Manhattan to reach their destination.

- In addition, the volume of traffic across the OD pairs between these two regions is high increasing the criticality of the facilities which carry traffic between Manhattan and New Jersey. While this is not surprising, the proposed methodology clearly provides a ranking of the different facilities which can potentially be used for making investments to relieve congestion or improve safety/security.

TABLE 7. RESULTS

ID	Facility Name	Direction	Crit. Ratio		V/C Ratio	
			Value	Ranking	Value	Ranking
90849	Lincoln Tunnel	To Manhattan	52.63	1	5.25	1
90845	Holland Tunnel – EB	To Manhattan	39.73	2	3.15	9
90578	Queensboro Bridge	To Manhattan	14.76	3	1.27	21

[2] We have assessed the criticality of the George Washington Bridge manually. That is we computed the criticality ratio of the Geroge Washington Bridge disrupting all the sections that carries flow to Manhattan and manually using TransCAD to run the traffic assignment. The preliminary results show that the criticality ratio rises to 121.3.

ID	Facility Name	Direction	Crit. Ratio		V/C Ratio	
160403	Queensboro Bridge	To Queens	10.87	4	1.32	19
90857	G. Washington Bridge	To Manhattan	7.43	5	1.32	8
90861	G. Washington Bridge	To Manhattan	7.43	6	3.40	18
59782	Williamsburg Bridge – WB	To Manhattan	6.59	7	1.36	17
210123	Queens Midtown Tunnel – WB	To Manhattan	6.47	8	2.35	12
90850	Lincoln Tunnel	To New Jersey	5.75	9	2.88	10
90378	Brooklyn Battery Tunnel		5.34	10	0.63	25
90207	Brooklyn Bridge – EB	To Brooklyn	4.79	11	1.16	23
62215	Croxx Bronx Exp. Bridge –EB	To Bronx	4.16	12	3.55	3
58250	Manhattan Bridge		4.13	13	1.20	22
90846	Holland Tunnel – WB	To New Jersey	3.98	14	5.25	2
58212	Brooklyn Bridge –WB	To Manhattan	3.57	15	3.78	7
90318	Williamsburg Bridge – EB	To Brooklyn	2.49	16	2.29	13
61966	Macombs Dam Bridge	Manhattan-Bronx	2.24	17	2.08	15
90854	G. Washington Bridge	To Manhattan	2.03	18	3.90	5
90863	G. Washington Bridge	To Manhattan	2.03	19	2.23	14
90856	G. Washington Bridge	To New Jersey	0.85	20	3.90	6
90862	G. Washington Bridge	To New Jersey	0.85	21	1.67	16
62217	Croxx Bronx Exp. Bridge –WB	To Manhattan	0.78	22	2.76	11
60160	Queens Midtown Tunnel – EB	To Queens	0.77	23	4.26	4
90858	G. Washington Bridge	To New Jersey	0.37	24	0.78	20
90860	G. Washington Bridge	To New Jersey	0.37	25	1.32	24

Another important remark is to confirm that there are only a few critical infrastructures which contribute to the greatest loss in travel time (economy) in the region. The disruption of most of the other infrastructures only produces a moderate increase in the increase in travel time. However, the disruption of a few infrastructures produces a large increase in travel time. This can be observed in Figure 7 which presents the map of the region and where only a few links have a thick red line (the criticality of the link in the map is represented by the thickness of the link) and it is summarized in Figure 6. Therefore, our efforts can be focused to improve the resilience of these facilities and our criticality measure can be used to identify these facilities.

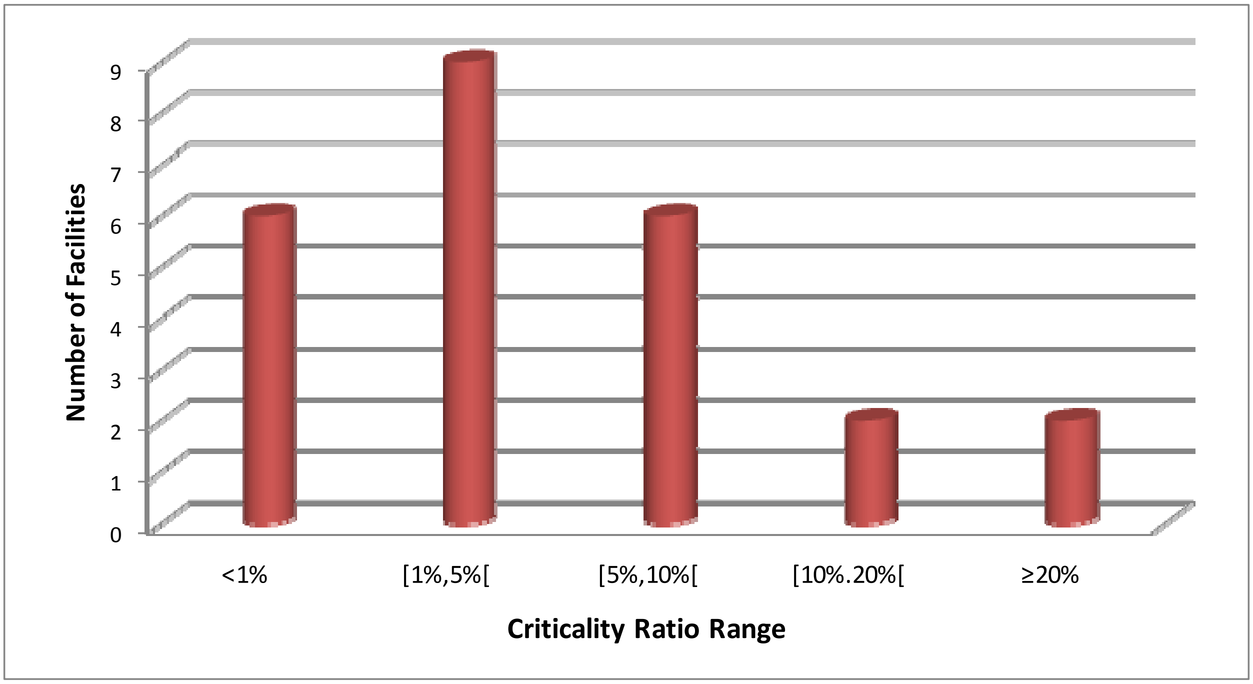


Figure 6. Number of Facilities by Range of criticality ratio

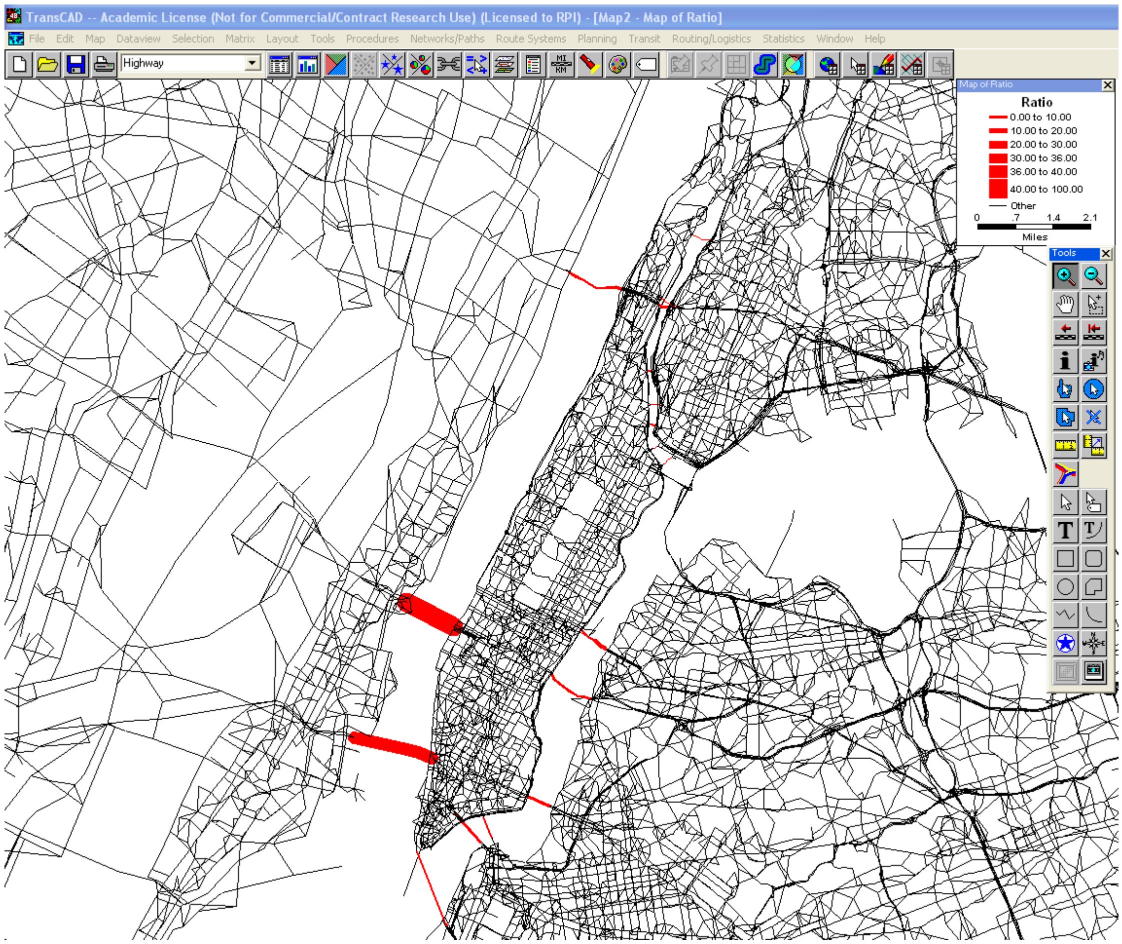


FIGURE 7. RESULTS SHOWN IN THE TRANSCAD NETWORK

The last analysis is a comparison of our criticality measure with a traditional measure in transportation, the V/C ratio. When planning the increase in capacity of a link, the V/C ratio is a common measure to define the level o service of the facility. We want to evaluate if this measure also captures the criticality of a link comparing our criticality measure with the V/C ratio in the original network (without disruption), see Table 7. Our intuition can lead us to think that links with larger V/C ratios are the most critical.

In assessing criticality, the situation is different. By observing the values in Table 7, we can note that the V/C ratio cannot capture the effect of route change decision after the disruption. The ranking is different from the one using our criticality measure. For instance the Holland tunnel bound to Manhattan is ranked 9 and the bound to New Jersey is ranked 2nd which contradicts the fact that we are using the AM Peak OD Matrix and we can expect that the bound to Manhattan be more critical.

This is corroborated by observing the correlation between the V/C ratio and our criticality measureThis is corroborated by observing the correlation between the V/C ratio and our criticality measure. The correlation between our criticality measure and the V/C ratio is not strong enough (see Figure 8) to show that the V/C ratio cannot be used instead of our criticality measure.

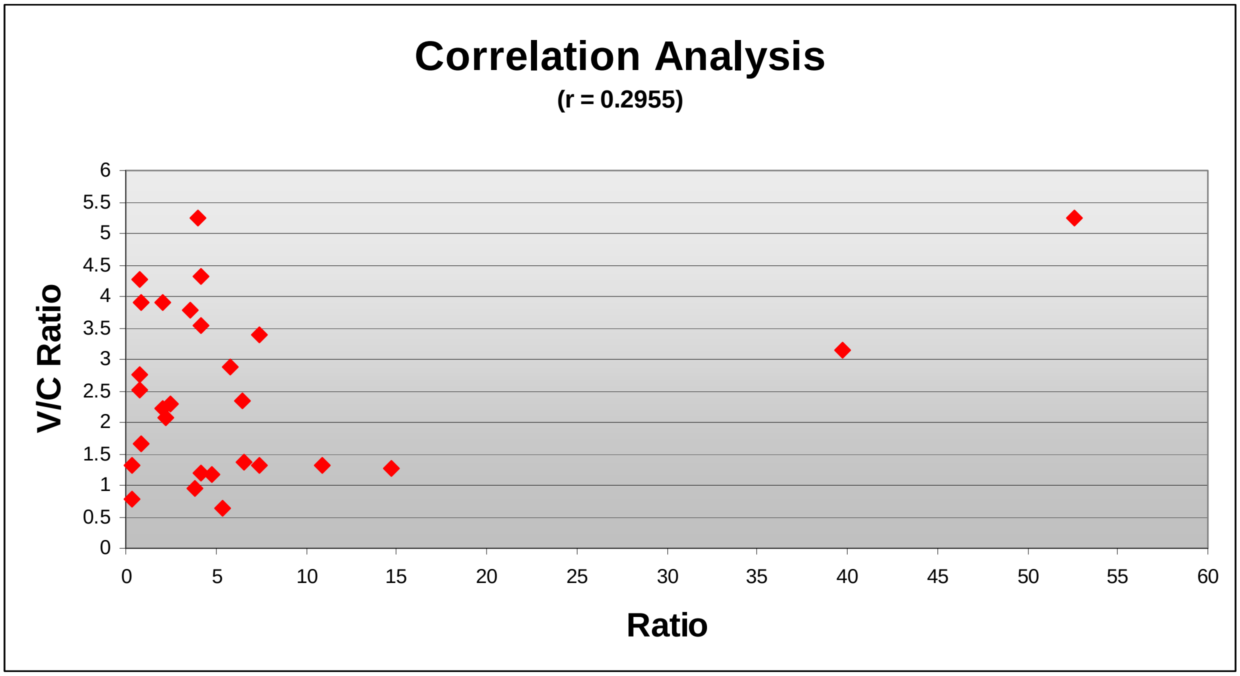


FIGURE 8. CORRELATION ANALYSIS

Chapter 9 CHAPTER 6: Conclusions

Knowing the criticality of either a link or a node is important because it could drive our investment decisions in the future; in this project we provide:

- An extensive revision of current methodologies to assess criticality in a network both by practitioners and scholars.
- A practical solution for assessing the criticality of transportation infrastructure in a transportation network using a developed measure of criticality that captures the congestion effects.
- A TransCAD macro that allows assessing the criticality in large networks through the use of the Frank-Wolfe algorithm for determining the User Equilibrium solution.
- An application to assess Manhattan main access infrastructures using a network that includes New Jersey, Bronx, Queens, Brooklyn and Manhattan.
- A comparison with the V/C ratio and clearly our criticality measure out-performs the V/C ratio as a criticality measure. This is mainly because the V/C ratio does not include driving behavior which, in some sense, is captured in the traffic assignment included in our measure. In contrast with the results of our criticality measure, not all the facilities that are going into Manhattan are shown as critical, indicating that just using the V/C ratio is not a good measure to assess criticality in transportation infrastructure.

In terms of the specific application to the Manhattan network:

- The disruption of few links represents a higher impact in the travel time of the entire network making them the most critical facilities in the network. The results from this methodology can help us to make strategic transportation investments for creating redundancies or hardening infrastructures. While the question of how much to invest is still not fully answered, an approximation investment scheme is to invest the resources based on the fraction of total travel reduction due to the loss of the facility.
- Since the AM peak time has been evaluated, we found that all sections that provide the access to Manhattan from New Jersey are more critical. These two areas have fewer alternatives (in terms of modes of transportation) as compared with Bronx, Brooklyn or Queens
- The methodology developed in this project can be further extended to developed a tool to decide how much to invest and also extend to incorporate rigorous economic measures of transportation externalities due to freight and passenger traffic.

Chapter 10 References

1. Bar-Noy, Amotz., Samir Kuller, and Baruch Schieber. The Complexity of Finding the Most Vital Arc and Nodes. Technical Report CS-TR-3539, University of Maryland, Institute for Advanced Computer Studies, MD, 1995.

2. Barton, A. Addressing The Problem Of Finding A Single Vital Edge In A Maximum Flow Graph. National Research Council Canada, 2005. Available online at http://iit-iti.nrc-cnrc.gc.ca/iit-publications-iti/docs/NRC-48305.pdf. Accessed on 1st March 2007.

3. Chen, Anthony, Sirisak Kongsomsaksakul, and Zhong Zhou, Assessing Network Vulnerability using a Combined Travel Demand Model. CD-ROM. Transportation Research Board of the National Academies, Washington, D.C., 2007.

4. Cho, S., Gordon, P., Moore II, J.E., Richardson, H.W., Shinozuka, M., and Chang, S., Integrating Transportation Network and Regional Economic Models to Estimate the Costs of a Large Urban Earthquake", Journal of Regional Science, 41(1), 39-65, 2001.

5. Church, Richard L., Maria P. Scaparra, and Richard S. Middleton. Identifying Critical Infrastructure: The Median And Covering Facility Interdiction Problems. In Annals of the Association of American Geographers, Vol. 94(3), pp. 491–502, 2004

6. Cormican, Kelly J., David P. Morton, R. Kevin Wood. Stochastic Network Interdiction. In Operations Research, Vol. 46, No. 2, March-April, 2008.

7. Department of Homeland Security, National Infrastructure Protection Plan, 2006. Available Online at http://www.dhs.gov/xlibrary/assets/NIPP_Plan.pdf, Accessed: Mar 01, 2007.

8. Grubesic, Tony. H., and Alan T. Murray, Vital Nodes, Interconnected Infrastructures, And The Geographies Of Netwrork Surviva-Bility, In Annals of the American Geographers, Vol. 96 (1), pp. 64-83, 2006.

9. Ham, Douglas B., and Stephen Lockwood, National Needs Assessment for Ensuring Transportation Infrastructure Security – Contractor's Final Report, Requested by American Association of State Highway and Transportation Officials (AASHTO) Transportation Security Task Force, 2002. Available Online at http://freight.transportation.org/doc/NCHRP_B.pdf, Accessed: Mar 01, 2007.

10. Karaca, E., Regional Earthquake Loss Estimation: Role of Transportation Network, Sensitivity and Uncertainty, And Risk Mitigation, Ph.D. dissertation, Massachusetts Instt. Of Technology, June 2005.

11. Kim, T.J., Ham, H., and Boyce, D.E., Economic Impacts of Transportation Network Changes: Implementation of a Combined Transportation Network and Input-Output Model, Papers in Regional Science, 81, 223-246, 2002.

12. Latora, Vito., and Massimo Marchiori. Efficient Behavior of Small Networks, Physical Review E, Vol. 87, 2001.

13. Latora, Vito., and Massimo Marchiori. Vulnerability And Protection Of Infrastructure Networks, Physical Review E, Vol. 71, 2005.

14. Liu, Changzheng., and Yue Yue Fan, A Two-Stage Stochastic Programming Model For Transportation Network Retrofit. CD-ROM. Transportation Research Board of the National Academies, Washington, D.C., 2007.

15. Matisziw, Timothy. C., Alan T. Murray, and Tony H. Grubesic. Evaluating Vulnerability and Risk in Interstate Highway Operation. CD-ROM. Transportation Research Board of the National Academies, Washington, D.C., 2007.

16. Modarres1, M., and B Zarei. Application Of Network Theory And Ahp In Urban Transportation To Minimize Earthquake Damages, Journal of the Operational Research Society, Vol. 53, pp. 1308-1316, 2002.

17. Murray-Tuite, P.M., Identification of vulnerable transportation infrastructure and household decision making under emergency evacuation conditions, Ph.D. dissertation, Univ. of Texas, Austin, Dec. 2003.

18. Nagurney, Anna, Qiang, Qiang. A Netwrok Efficiency Measure with Application to Critical Infrastructuer Networks, Jounral of Global Optimization, Vol. 40, pp. 261-275, 2008.

19. NCHRP Project 20-07, A Guide to Highway Vulnerability Assessment for Critical Asset Identification and Protection – Contractor's Final Report, Requested by American Association of State Highway and Transportation Officials (AASHTO) Transportation Office Security Task Force, 2002. Available Online at http://www.transportation.org/sites/security/docs/NatlNeedsAssess.pdf, Accessed: Mar 01, 2007.

20. NCHRP REPORT 525 Volume 11, Disruption Impact Estimating Tool–Transportation (DIETT): A Tool for Prioritizing High-Value Transportation Choke Points, 2006. Available Online at http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_rpt_525v11.pdf, Accessed: Mar 01, 2007.

21. North American Transportation Atlas Data (NORTAD) CD. Available from http://ww.bts.gov/publications/north_american_transportation_atlas_data

22. New York State. Traffic Data Viewer. Available from https://www.nysdot.gov/portal/page/portal/divisions/engineering/applications/traffic-data-viewer

23. Qiao, Jianhong ., David Jeong, Mark LAwley, Jean-Phillippe P. Richard, Dulcy M. Abraham and Yuehwern Yih. Allocating Security Resources To A Water Supply Network. In IIE Transactions, Vol. 39, pp. 95-109, 2007.

24. Ratliff, H. Donald., G. Thomas Sicilia, S. H. Lubore. Finding The N Most Vital Links In Flow Networks, Management Science, Vol 21 (5), pp. 531, 1975.

25. Shen, Hong. Finding The *K* Most Vital Edges With Respect To Minimum Spanning Tree. Acta Informatica 36, pp. 405–424, 1999.

26. Scott, D.M., Novak, D., Aultman-Hall, L., and Guo, F., A New Approach for Identifying Critical Links in Transportation Networks, CD-ROM. Transportation Research Board of the National Academies, Washington, D.C., 2006.

27. TCRP REPORT 86/NCHRP REPORT 525 Volume 12, Making Transportation Tunnels Safe and Secure, 2006. Available Online at http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_rpt_525v12.pdf, Accessed: Mar 01, 2007.

28. Wood, Kevin R., Deterministic Network Interdiction, Mathematical and Computer Modeling, Vol. 17, pp. 1-18, 1993.

Chapter 11 Appendix: GISDK Code Details

In this section we provide more details of the GISDK code implemented in Transcad, we follow the same organization as in Section 2. We use the Manhattan network example that is included in the CD.

Data Base Preparation

General Steps

1. Obtain the structure of the table:

    - Line 3: As mentioned in the General Steps, line 3 obtains the table structure of the layer Highway. It is important to see that the Line Layer **must** have the name **Highway**. If your network does not have this name you **must** change it going to the button **Map Layers** and choose the option **Rename**. This is very important since this affects most of the references to this layer in the rest of the procedures and sentences, i.e.: Line Layer is also called Highway (lines 2, 14, 23, 28, 29, 30, 33).

2. Create a temporal field to store the capacity of the selected links (lines 4 -11):

    - Line 9: The temporary capacity field (**Temp**) has a Type "Real of width 12 and 2 decimals". This can be changed depending on the type that the Capacity field has. To change it just change it to integer, just write {{"Temp", "Integer", 10, 0, True, , , , , , , null}}

3. Create the field where we store the ratio that indicates the criticality (lines 14 -22, see Figure in Appendix):

    - Lines 9 and 14: struct and struct2 are the variables used to change the streucture of the table adding the fields Temp and Ratio.

4. The field Ratio contains the ratio that is used to evaluate the critical links.
5. Obtain the IDs of the selected links:

    - Line 23: **listasel** is a variable created to store the Ids of the selected links.

6. Using the selected links copy all the capacity values in the Temporal field and copy them into a txt file (see lines 23-26):

    - Lines 24 and 26: In these lines we store the position of the records of the Ids of the selected links and the capacity of this selection respectively. To change the path where you want to store the txt's files just modify the paths (see highlighted sentence In the corresponding line), i.e.: ptr = OpenFile("**PATH**", "w")

7. For all the selected links, copy the values of the Capacity field of the Highway layer into the Temporal field of the Highway layer (lines 27-34 in Figure in Appendix, see Figure in Appendix).

   - Lines 29 and 30: Note that in these lines we are using the name **Capacity** because we are assuming that the name of the field that contains the capacity is **Capacity** if you have a different name in your line layer it is necessary to go to the option **Modify Table** in the menu Dataview and change it.

```
1    Macro "Database Preparation"
2    // Adding temporary field to store original capacity values///
3    strct = GetTableStructure(Highway)
4    for i = 1 to strct.length do
5        // Copy the current name to the end of strct
6        strct[i] = strct[i] + {strct[i][1]}
7    end
8    // Add a temporary Capacity field
9    struct = strct + {{"Temp", "Real", 12, 2, True, , , , , , , null}}
10   // Modify the table
11   ModifyTable(view_name, struct)
12   // Adding temporary field to store the ratio in travel time///
13   // field name: Ratio
14   strct2 = GetTableStructure(Highway)
15   for i = 1 to strct.length do
16       // Copy the current name to the end of strct
17       strct2[i] = strct2[i] + {strct2[i][1]}
18   end
19   // Add a temporary Ratio field
20   struct2 = strct2 + {{"Ratio", "Real", 12, 2, True, , , , , , , null}}
21   // Modify the table
22   ModifyTable(view_name, struct2)
23   listasel = GetSetIDs("Highway|Selection")
24    ptr = OpenFile("C:\\Program Files\\TransCAD\\0_Base\\id_links.txt","w")
25    WriteArray(ptr, listasel)
```

```
ptr2 = OpenFile("C:\\Program Files\\TransCAD\\0_Base\\cap_id_links.txt", "w")
for i=1 to listasel.length do
        rh1 = LocateRecord("Highway|","ID",{listasel[i]} ,)
        value = GetRecordValues("Highway", rh1, {"ID", "Capacity"})
        flds = {"Highway.Capacity"}
        vals = GetFieldValues(flds, null)
        WriteArray(ptr2,vals)
        SetRecordValues("Highway",rh1,{{"Temp",vals[1]}})
end
Endmacro
```

FIGURE 9. MACRO DATABASE PREPARATION

Base Case

1. Network building operation: The network building operation is a TransCAD procedure that creates a network file that is used in the traffic assignment procedure. Highlighted in Figure 10 are some of the sentences can be changed, other commands cannot be changed. Here are some details about the code:
    - Line 3: RunMacro("TCB Init") initializes the procedure and is a reserved sentence in TransCAD that cannot be modified.
    - Line 5: It reads the link set. It goes to the path and reads the Highway layer in the database. In the provided example the database name is **HN050131.DBD** and the line layer is Highway. Note that the sentence **C:\\Path…\\ HN050131.DBD|Highway** contains the symbol "|" that indicates the Highway layer.
    - Lines 6 and 7: Both read the Ids of the nodes and links respectively.
    - Line 11: This large sentence indicates all the fields in the Highway layer that will be used in the network file. It is not necessary to include all the fields, only the fields mentioned in Table 2 are actually needed.
    - Line 12: It creates an output file called **SP.net**
    - Line 13: It contains the execution command for the network building operation (do not make any change in this line).
2. Traffic Assignment Procedure: The traffic assignment needs three inputs: The Database, the network file and the OD Matrix file. In addition, it needs to input the fields that contain the Free Flow Speed, the Capacity and the Alpha and Beta parameters. More details are presented here:
    - Line 16: Contains the path where the database file is stored.

- Line 17: Contains the path of the network file.
- Line 18: Contains the path of the OD matrix. Note that at the end of this sentence there are three “ID”. The first two are the ID of the origin-destination and the third is just one default name for the field for the values of the matrix (see the Section for creating and OD Matrix).
- Lines 19-23: In these sentences we need to write the name of the fields that contain the free flow speed, capacity, alpha and beta.
- Lines 24 and 25: Line 24 specifies the convergence rate and line 25 the maximum number of iterations.
- Line 26: This sentence creates and output file with the name **ASN_LinkFlow2.bin** in the corresponding path.
- Line 27: It contains the execution command for the traffic assignment procedure (do not make any change in this line)

```
1	Macro "Base Case"
2	//Bulding Network 1
3	  RunMacro("TCB Init")
4	   Opts = null
5	   Opts.Input.[Link Set] = {"C:\\Program Files\\TransCAD\\0_Base\\HN050131.DBD|Highway", "Highway"}
6	   Opts.Global.[Network Options].[Node ID] = "[Highway Node].ID"
7	   Opts.Global.[Network Options].[Link ID] = "Highway.ID"
8	   Opts.Global.[Network Options].[Turn Penalties] = "Yes"
9	   Opts.Global.[Network Options].[Keep Duplicate Links] = "FALSE"
10	   Opts.Global.[Network Options].[Ignore Link Direction] = "FALSE"
11	   Opts.Global.[Link Options] = {{"Length", "Highway.Length", "Highway.Length"}, {"ID", "Highway.ID", "Highway.ID"}, {"Length", "Highway.Length", "Highway.Length"}, {"Dir", "Highway.Dir", "Highway.Dir"}, {"[ID:1]", "Highway.[ID:1]", "Highway.[ID:1]"}, {"TOT_LANE", "Highway.TOT_LANE", "Highway.TOT_LANE"}, {"Alpha", "Highway.Alpha", "Highway.Alpha"}, {"Beta", "Highway.Beta", "Highway.Beta"}, {"Capacity", "Highway.Capacity", "Highway.Capacity"}, {"FF", "Highway.FF", "Highway.FF"}}
12	   Opts.Output.[Network File] = "C:\\Program Files\\TransCAD\\0_Base\\SP.net"
13	  ret_value = RunMacro("TCB Run Operation", 1, "Build Highway Network", Opts)
14	// STEP 0: Assignment
15	Opts = null
16	   Opts.Input.Database = "C:\\Program Files\\TransCAD\\0_Base\\HN050131.DBD"
```

```
17         Opts.Input.Network = "C:\\Program Files\\TransCAD\\0_Base\\SP.net"
18         Opts.Input.[OD Matrix Currency] = {"C:\\Program Files\\TransCAD\\0_Base\\highway_am.mtx",
       "QuickSum", "Rows", "Columns"}
19         Opts.Field.[FF Time] = "FF"
20         Opts.Field.Capacity = "Capacity"
21         Opts.Field.Alpha = "Alpha"
22         Opts.Field.Beta = "Beta"
23         Opts.Field.Preload = "None"
24         Opts.Global.Convergence = 0.1
25         Opts.Global.Iterations = 30
26         Opts.Output.[Flow Table] = "C:\\Program Files\\TransCAD\\0_Base\\ASN_LinkFlow2.bin"
27                 ret_value = RunMacro("TCB Run Procedure", 1, "Assignment", Opts)
28     Endmacro
```

FIGURE 10. MACRO FOR BASE CASE TRAFFIC ASSIGNMENT

Network Assessment

- Computing Total Travel Time for Base Case (lines 2-5):
    - Line 2: Opens the **ASN_LinkFlow2.bin** file and assigns this file to the variable **ans**.
    - Line 3: Obtains the vector of values in the field **TOT_VHT**. This is a default field created for the Traffic Assignment Procedure that stores the total travel time.
    - Line 4: Compute the summation of these values to obtain the total travel time and stores the value in the variable **sum1**.
    - Line 5: Closes the file **ASN_LinkFlow2.bin**.
- Lines 6-12: These sentences open the txt files that have the id of the selected links.
- Line 10: Starts the loop for all the selected links.
- Line 11: j is the variable that is user as a counter for the procedure and operations in lines 28 and 41.
- Change of capacity (lines 12-16): These sentences changes the capacity of the selected links to 1 (see Line 16).
- <u>Network building operation</u> (lines 18-28): Same as explained in the **Base Case.**
- <u>Traffic Assignment Procedure</u> (lines 30-42):Same as explained in the **Base Case.**
- Lines 43-46: Restores the original values of the capacities (see Line 45).

- Computing Total Travel Time for Base Case (lines 47-50): Same as Lines 2-5:
    - Line 47: Opens the **ASN_LinkFlow2.bin** file and assigns this file to the variable **ans**.
    - Line 48: Obtains the vector of values in the field **TOT_VHT**. This is a default field created for the Traffic Assignment Procedure to store the total travel time.
    - Line 49: Compute the summation of these values to obtain the total travel time and stores the value in the variable **sum**.
    - Line 50: Closes the file **ASN_LinkFlow2.bin**.
- Line 51: Computes the Ratio **sum/sum1** in percentage value and saves it in the variable **ra**.
- Line 52: Saves the result in the field **Ratio** for the current link analyzed.
- Line 53: Increases the counter j.
- Line 54: Ends up the loop.

```
1	Macro "Network Assessment"
2	ans= OpenTableEx("ans", "FFB", {"C:\\Program Files\\TransCAD\\0_Base\\ASN_LinkFlow2.bin"},
	{{"Shared","True"}})
3	 v=GetDataVector(ans+"|", "TOT_VHT",)
4	 sum1 = VectorStatistic(v,"Sum",)
5	CloseView(ans)
6	listasel = GetSetIDs("Highway|Selection")
7	ptr = OpenFile("C:\\Program Files\\TransCAD\\0_Base\\id_links.txt", "w")
8	 WriteArray(ptr, listasel)
9	ptr2 = OpenFile("C:\\Program Files\\TransCAD\\0_Base\\cap_id_links.txt", "w")
10	for i=1 to listasel.length do
11	   j = 2
12	   rh2 = LocateRecord("Highway|","ID",{listasel[i]} ,)
13	     value2 = GetRecordValues("Highway", rh2, {"ID", "Capacity"})
14	     flds2 = {"Highway.Capacity"}
15	     vals2 = GetFieldValues(flds2, null)
16	   SetRecordValues("Highway",rh2,{{"Capacity",1}})
17	//Bulding Network
18	   RunMacro("TCB Init")
19	    Opts = null
```

```
    Opts.Input.[Link Set] = {"C:\\Program Files\\TransCAD\\0_Base\\HN050131.DBD|Highway", "Highway"}
    Opts.Global.[Network Options].[Node ID] = "[Highway Node].ID"
    Opts.Global.[Network Options].[Link ID] = "Highway.ID"
    Opts.Global.[Network Options].[Turn Penalties] = "Yes"
    Opts.Global.[Network Options].[Keep Duplicate Links] = "FALSE"
    Opts.Global.[Network Options].[Ignore Link Direction] = "FALSE"
    Opts.Global.[Link Options] = {{"Length", "Highway.Length", "Highway.Length"}, {"ID", "Highway.ID", "Highway.ID"}, {"Length", "Highway.Length", "Highway.Length"}, {"Dir", "Highway.Dir", "Highway.Dir"}, {"[ID:1]", "Highway.[ID:1]", "Highway.[ID:1]"}, {"TOT_LANE", "Highway.TOT_LANE", "Highway.TOT_LANE"}, {"Alpha", "Highway.Alpha", "Highway.Alpha"}, {"Beta", "Highway.Beta", "Highway.Beta"}, {"Capacity", "Highway.Capacity", "Highway.Capacity"}, {"FF", "Highway.FF", "Highway.FF"}}
    Opts.Output.[Network File] = "C:\\Program Files\\TransCAD\\0_Base\\SP.net"
ret_value = RunMacro("TCB Run Operation", j, "Build Highway Network",Opts)
// STEP j: Assignment
Opts = null
    Opts.Input.Database = "C:\\Program Files\\TransCAD\\0_Base\\HN050131.DBD"
    Opts.Input.Network = "C:\\Program Files\\TransCAD\\0_Base\\SP.net"
    Opts.Input.[OD Matrix Currency] = {"C:\\Program Files\\TransCAD\\0_Base\\highway_am.mtx", "QuickSum", "Rows", "Columns"}
    Opts.Field.[FF Time] = "FF"
    Opts.Field.Capacity = "Capacity"
    Opts.Field.Alpha = "Alpha"
    Opts.Field.Beta = "Beta"
    Opts.Field.Preload = "None"
    Opts.Global.Convergence = 0.1
    Opts.Global.Iterations = 30
    Opts.Output.[Flow Table] = "C:\\Program Files\\TransCAD\\0_Base\\ASN_LinkFlow2.bin"
ret_value = RunMacro("TCB Run Procedure", j, "Assignment", Opts)
value3 = GetRecordValues("Highway", rh3, {"ID", "Capacity"})
        flds3 = {"Highway.Temp"}
        vals3 = GetFieldValues(flds3, null)
SetRecordValues("Highway",rh2,{{"Capacity",vals3[1]}})
```

```
ans2=OpenTableEx("ans2", "FFB", {"C:\\Program Files\\TransCAD\\0_Base\\ASN_LinkFlow2.bin"}, {{"Shared","True"}})
      v=GetDataVector(ans2+"|", "TOT_VHT",)
            sum=VectorStatistic(v, "Sum",)
CloseView(ans2)
ra = ((sum/sum1)-1)*100
    SetRecordValues("Highway",rh42,{{"Ratio",ra}})
j=j+1
end
ShowMessage("Done")
Endmacro
```

FIGURE 11. MACRO FOR NETWORK ASSESSMENT