

# EXPERIMENTAL COMPARISON OF HYBRID AND PROACTIVE MANET ROUTING PROTOCOLS

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## ABSTRACT

*This paper describes an experimental implementation of a QoS-aware hybrid routing protocol that uses a flexible mix of proactive and reactive routing techniques within Mobile Ad hoc Networks (MANETs). After a brief review of the benefits and applications of proactive, reactive (on-demand) and hybrid routing, the architectural details and protocol operation of SRC's "Wireless Ad hoc Routing Protocol" (WARP) are given. This paper then discusses the laboratory testing methodology used during the development of WARP, and gives an experimental comparison of WARP with a proactive routing protocol – namely Optimized Link State Routing (OLSR).*

## INTRODUCTION

Current Internet routing protocols such as Open Shortest Path First (OSPF) were developed for the fixed Internet backbone where routers are bolted to the ground. It is well-known that OSPF fails in mobile wireless environments because it attempts to continuously track every change in the network topology. In wireless environments, OSPF's "proactive" approach to routing causes wasted overhead that often saturates the wireless medium with control traffic for routes that are never used. As such, there has been extensive research on new routing protocols for the "Mobile Ad hoc Networks (MANETs)" projected for next-generation military networks.

MANETs differ from wired Internet Protocol (IP) networks in several respects. Ad hoc networks lack the centralized infrastructure found in both cellular and fixed networks. Nodes and infrastructure may be highly mobile. Second, there is a blurring of IP's typical distinction between routers and hosts. Third, most military MANETs have low bandwidth (kbps) wireless links and battery-operated nodes that require power-efficient operation.

## Taxonomy of MANET Routing Protocols

Existing IP routing protocols can be classified either as "proactive" or "reactive". Proactive protocols attempt to continuously evaluate all of the routes within a network – so that when a packet needs to be forwarded, a route is already known and can be used immediately. OSPF is an example of a Proactive Routing Protocol (PRP) for wired IP backbone networks. MANET-specific examples include Optimized Link State Routing (OLSR) [1], Topology Broadcast based on Reverse Path Forwarding (TBRPF) [2] and Hazy Sighted Link State Routing [3]. In contrast, Reactive Routing Protocols (RRPs) invoke a route determination procedure "on-demand" only. Thus, if route is needed then some sort of global-search procedure is employed. The classical flood-search algorithms are simple reactive-protocols. MANET-optimized examples include Ad hoc On-Demand Distance Vector (AODV) [4] and Dynamic Source Routing (DSR) [5].

It is well-known that proactive-protocols are not optimal for either MANETs that have rapidly changing topologies or sensor networks that require emission control (EMCON) modes-of-operation. However, purely reactive protocols are often inappropriate for several common MANET topologies such as cluster-based networks and relatively static networks. In addition, reactive protocols introduce additional latency (and possibly overhead) for real-time traffic. As such, "hybrid" or "zone" routing protocols that use a mix of both proactive and reactive routing techniques at each network node have been proposed. One example is Cornell's Zone Routing Protocol (ZRP) [6].

After a brief theoretical comparison of proactive, reactive and hybrid routing protocols, this paper describes SRC's "Wireless Ad hoc Routing Protocol (WARP)". WARP is based on Cornell's ZRP, with additional enhancements for Quality of Service (QoS) support. (Note: WARP resulted from an SRC, Cornell and AFRL collaboration during 1999.) The next two sections then describe this paper's

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test-bed procedures and an experimental comparison of WARP and OLSR.

### Theoretical Comparisons of MANET Routing Protocols

There have been theoretical comparisons of proactive, reactive and hybrid routing protocols. In Ref. [7], the “total routing overhead” is the Figure-of-Merit. For proactive protocols that overhead includes the number of packets being exchanged between nodes in order to maintain a consistent set of forwarding tables at each network node. For reactive protocols, that overhead includes the bandwidth consumed by the Route Request/Reply messages. For all three types of protocols, the analysis includes the overhead caused by “sub-optimal routes” that are not the minimum number of hops. Their comparison of HSLs, DSR and ZRP then showed that (for fairly uniform node densities and traffic patterns) the asymptotic overhead for proactive, reactive and hybrid routing scaled as  $O(N^{1.5})$ ,  $O(N^2)$  and  $O(N^{1.66})$ , respectively, in large N-node networks. However, that work also noted that ZRP might have superior scaling performance with respect to traffic load, non-uniform traffic patterns, and mobility-rates.

On a much more qualitative basis, make the following definitions:

- $N$  = number of nodes in network
- $L$  = average path length (in hops)
- $R$  = average number of active routes per node
- $\mu$  = average number of link-breakages per second
- $\alpha$  = “route activity” = new route requests/second generated by each node
- $\rho$  = “route concentration factor” = average % of each node’s active routes that use each link

$R$  measures the number of other nodes that each node has active data-plane communications with. For example, the gateway router at a Tactical Operations Center (TOC) may have a high value of  $R$ , while an individual soldier might have a much smaller one. The parameter  $\mu$  is an indication of how fast the nodes are moving with respect to each other, since those nodes probably experience more frequent changes in their RF (and hence network-layer) connectivity. (Note: fast-moving nodes, such as squad of jeeps, may actually have a small value of  $\mu$  if their relative movement is low.) The parameter  $\alpha$  measures two separate effects. The first is how fast a given node changes its set of destination nodes. The other is the holding time of a node’s IP sessions, since the RRP route-caches eventually “timeout” unused routes. Hence, one long application-layer session generates less RRP overhead than several widely-spaced, but shorter sessions.

Finally, the  $\rho$  parameter accounts for traffic hot-spots within the MANET. As shown below, the presence of those hotspots favors proactive routing. The  $\rho$  parameter also accounts for the fact that a given link-breakage may not cause a given route to break. So, a low  $\rho$  favors reactive routing.

For (un-optimized) proactive routing, each link-state change must be propagated to every other node over an average distance of  $L$ . As such, the total number of link-state update packets per second roughly scales as  $\mu*L*N^2$ . For (un-optimized) reactive routing, each route-search generates approximately  $N$  Route-Request packets. As such, the total number of route-request packets roughly scales as  $(\alpha + \rho*R*\mu)*L*N^2$  – where this formula includes the Route-Request messages due to both new routes ( $\alpha$ ) and also broken routes ( $\mu$ ). So, *as a very rough qualitative comparison*, reactive routing tends to generate less overhead than proactive routing if  $\mu*L*N^2 > (\alpha + \rho*R*\mu)*L*N^2$ , or  $1 > (\alpha/\mu) + \rho*R$ .

Qualitatively then, reactive routing is preferred over the more traditional proactive-routing techniques as the:

- a) Mobility goes up.
- b) Route concentration goes down.
- c) Number of active routes per node goes down.
- d) Route activity goes down.

Furthermore, zone routing (or any other clustering techniques) should improve on purely reactive-routing or purely proactive-routing if most traffic is localized (e.g., the  $\rho*R$  term is non-uniform).

This *rough* qualitative-analysis is intended to illustrate the design tradeoffs within MANET routing. Additional research is still required on quantitative analysis (and experimental verification) of protocol scaling with respect to the topology, mobility and traffic parameters defined above. Protocol evaluation when energy consumption and battery-life are the Figures-of-Merit is also an active research topic.

In general, hybrid routing’s flexibility allows the network operator to adjust the protocol operation to match the network’s current mission and state. For example, purely proactive operation might be used in relatively static networks such as inter-ship links. In contrast, purely reactive routing might be used in: a) dynamic networks such as clouds of tactical Unmanned Aerial Vehicles (UAVs) or b) networks of ground-based sensors that have strict Low Probability of Detection (LPD) requirements. These protocol adjustments could occur without changing

the network software or “rebooting” any of the underlying MANET routers [6]. This flexibility is a tradeoff against the added complexity of hybrid protocols. As such, the next section describes the complexity of SRC’s current software implementation of a hybrid routing protocol for MANETs.

### WIRELESS AD HOC ROUTING PROTOCOL

WARP is based on Cornell’s Zone Routing Protocol (ZRP) with additional enhancements for Quality of Service (QoS) support. The initial implementation of WARP provides best-effort routing and QoS routing based on link-stability and node-energy status. The software development took place on x86 PCs and Red Hat Linux (6.2, 7.1 and 7.2) with a subsequent port to Compaq iPAQ Personal Digital Assistants (PDAs) running Debian Linux on 206 MHz StrongARM processors. The WARP software requires no kernel modifications. During 2002, it is being ported to other operating systems/platforms such as Windows CE and the Joint Tactical Radio System (JTRS).

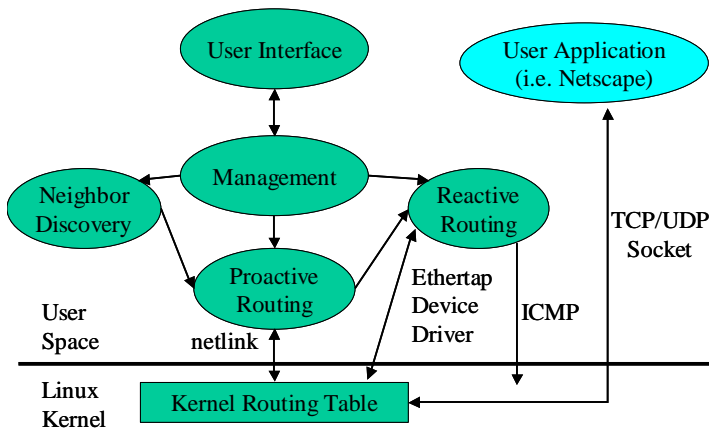


Figure 1. High-Level Software Architecture for WARP

WARP abides by standard IP layering practices. It commits no layering violations, and resides above a COTS TCP/IP stack. WARP performs its on-demand route discovery and maintenance using UDP datagrams. The interface to the Linux kernel’s routing tables then uses a clean, open interface (e.g., the netlink sockets library).

In brief, the WARP software’s functionality is broken up into several processes. WARP’s Neighbor Discovery Protocol (NDP) locates one-hop neighbors. WARP’s Proactive Routing Protocol (PRP) is a timer-based link-state routing protocol. It allows both best-effort routing based on hop-count and QoS routing based on wireless-specific routing metrics such as link-stability and “node energy status”. The “node energy status” metric allows preferential avoidance of routes through battery-operated

handheld radios – in favor of ones through vehicle-mounted radios and/or AC-powered radios.

WARP’s NDP and Reactive Routing Protocol (RRP) are separate from its PRP to allow flexibility in porting to handheld devices and microsensors. WARP’s RRP uses explicit source-routing that provides end-to-end QoS support in conjunction with PRP. Its major difference with DSR is that WARP’s RRP is a user-space application that should be more portable across operating systems. Its disadvantage is the added overhead associated with its UDP encapsulations for both data and control packets. (Note: the WARP software architecture is designed so that other group’s PRPs and RRP’s could be substituted for SRC’s protocols.)

WARP User Interface (UI) is currently a command-line interface (CLI) to the underlying processes. (Future plans include an SNMP interface and a Graphical User Interface.) Finally, WARP’s Management process reads the configuration files and configures (but does not modify) the underlying Linux kernel. It also provides the interface between the UI and the routing processes.

### TEST PROCEDURES AND SETUP

SRC implemented a network test-bed to study the performance of WARP and other MANET routing protocols – using actual TCP/IP stacks and routing code. The performance testing evaluated the ability of different MANET protocols to respond to changes in network topology. That testing measured the routing protocol overhead and packet-loss fraction.

Physical connectivity in the emulated network was modeled using the firewalling rules, provided by netfilter in the 2.4.x kernels, to configure each computer to drop packets from “non-neighbor” nodes. This approach allows emulated mobility in a mixed network of wired desktop PCs and wireless laptop PCs. (Note: other researchers have used similar techniques.)

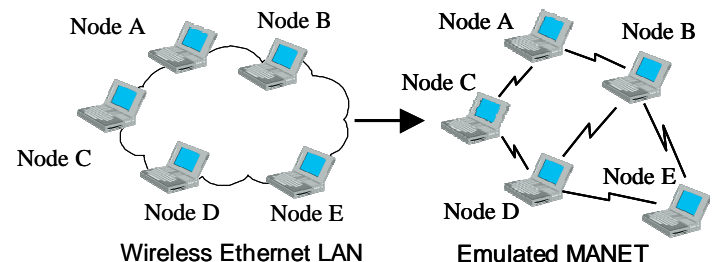


Figure 2. Lab Tests Use IP Firewall Rules to Enforce the Desired Connectivity Matrix

### Mobility Model

The lab tests used an ad hoc network of 14 nodes, whose initial *emulated* positions were chosen from a uniform random distribution over an area of 1000 m by 1000 m.

The tests used two mobility models – namely random motion and clustered motion. In the random-motion case, each node  $j$  was assigned a random destination that it moved towards at a constant speed,  $v$ , that was uniformly distributed between  $v_{\text{MIN}}$  and  $v_{\text{MAX}}$ . Once a node reached its destination, it paused for  $p$  seconds and then the process was repeated for a new random destination.

In the clustered model, each node belonged to a single, pre-defined cluster. Each cluster was assigned a random destination that it moved towards. The destinations for individual nodes within each cluster were chosen to be within  $R$  meters of the destination of the cluster's center. All nodes in a cluster then moved at the same randomly-chosen speed towards their destinations. Once all nodes in a cluster reached their destinations, the entire cluster paused for  $p$  seconds and the process was repeated. (Note: this paper's test-results used four clusters of sizes (4,4,3,3) nodes, respectively.)

### Routing Protocols

This paper compared the WARP software presented above against the Optimized Link State Routing (OLSR) Protocol. OLSR uses two techniques to reduce the overhead caused by link-state flooding. The first is multipoint Relays (MPRs). Each node selects several MPRs from its one-hop neighbors. The MPRs are chosen so that they can broadcast a link-state to all of that node's two-hop neighbors. The second technique is link-state reduction. A subset of the total number of link-states is flooded throughout the network. OLSR link-states only contain the links from a node to its MPRs; the other links are omitted. As such, OLSR is optimized for dense networks with slowly-changing topologies.

The OLSR code used for this paper was the 4/20/01 version (latest file timestamp) from the INRIA web-site. It implemented Version 3 of their Internet Draft. As such, both the OLSR code and the WARP code used in this paper's tests were prototype code that did not implement all of each protocol's features and optimizations.

### Traffic Sources and Traffic Models

The test-bed used ICMP Ping as the test-source. Each node's data rate was set at 64 kbps. This rate was representative of next-generation tactical data-rates. It also introduced minimal artifacts, into the test results, from the Ethernet and Wireless Ethernet MAC layers. (Note: both routing protocols used UDP packets for their control messages.)

After the networks were given 10 seconds to stabilize, each node began pinging another randomly selected node. In the clustered model, each node chose a target node in its cluster with probability  $P_C$  and a node in another cluster with probability  $(1 - P_C)$ . Each node continued to send Ping traffic to its target until the scenario concluded. (As such, the tests set the "route activity parameter",  $\alpha$ , basically to zero.)

### Physical Layer And MAC Model

The Media Access Control (MAC) protocols were the PC's actual Ethernet and Wireless Ethernet implementations. The total offered-load was chosen so that "Ethernet effects" did not measurably impact the data set's measured packet-loss rates.

The assumed transmission-range for the random motion model was 350m. For the clustered motion case, the intra-cluster range was equal to the cluster diameter (200m) and the inter-cluster radio had a 600m range. Packet delivery inside the transmission range was 100%, while nodes outside the range were deemed unreachable.

These parameters produced a fairly dense network with low mobility -- since SRC did not want to bias the test against proactive routing such as OLSR. For the random-motion case, each node had about 5 neighbors on average.

### EXPERIMENTAL RESULTS

The lab experiments presented below examined the effects of mobility, clustering and non-uniform traffic patterns on the performance of a hybrid MANET protocol (WARP) and a proactive MANET routing protocol (OLSR). Results are presented for best-effort routing only, since the OLSR prototype did not support QoS routing.

The Figures-of-Merits were the "packet-loss fraction" for the Echo Request (ICMP Ping) packets and the "number of overhead packets generated per successfully delivered data-packet". The second metric used overhead packets rather than overhead bytes because WARP's QoS features (which were not used in these tests) required larger link-state packets than OLSR. That second metric also reflected the overhead-costs associated with channel access in CSMA-based wireless networks. In all four graphs, the "range of node velocities" (shown on the X-axis) was the velocity-range (in meters per second) from which the parameter,  $v$ , was randomly chosen for each node for a given test-run. As such, each velocity-range produced a different network evolution from the same initial network "lay-down".

This paper's results are illustrative of the design tradeoffs between reactive, proactive and hybrid routing. They are not intended as a definitive evaluation of either WARP's

or OLSR's performance. Additional quantitative and theoretical work is required – especially for large networks, realistic operational scenarios and realistic propagation models.

### Packet-Loss Fraction

Figure 3 and Figure 4 show the relative packet-loss fractions for WARP and OLSR.

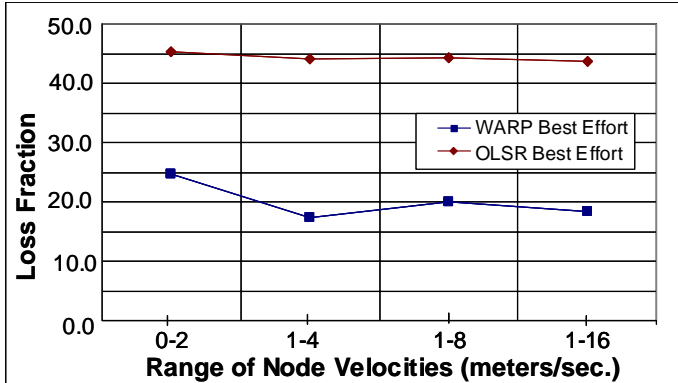


Figure 3. Packet-Loss Fraction for Random-Motion Tests

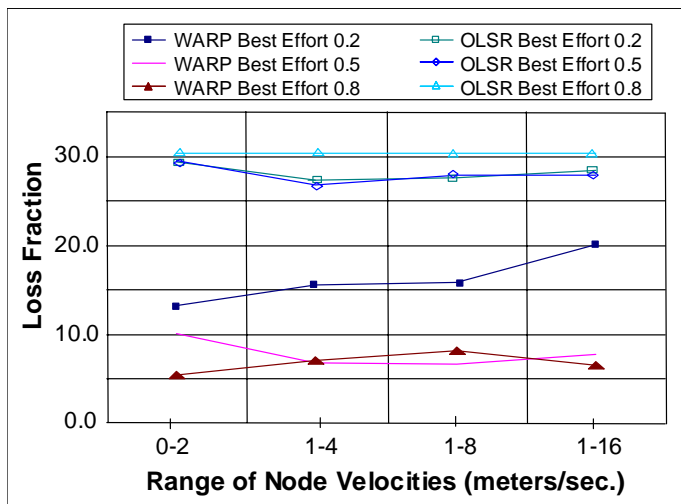


Figure 4. Packet-Loss Fraction for Clustered-Motion

In both the random-motion and clustered-motion tests, WARP's improved performance occurred partially because its RRP could "salvage" routes for in-flight packets that encountered a broken link within their routing zone. WARP could temporarily buffer several milliseconds of the Ping packets until either its RRP found a route or its PRP's link-state database settled back down.

For clustered motion, WARP's packet-loss fraction increased as the probability of inter-cluster traffic increased. This was an expected result since the average route-length increased and the benefits of PRP's local topology-information decreased as the probability ( $P_C$ ) of intra-cluster traffic decreased.

### Routing Overhead

For the random-motion case, WARP's lower packet-loss rates produced about 50 % higher overhead for the lowest mobility rate. This was mainly caused by the RRP route-salvaging techniques discussed above and the impact of the RRP source-route headers.

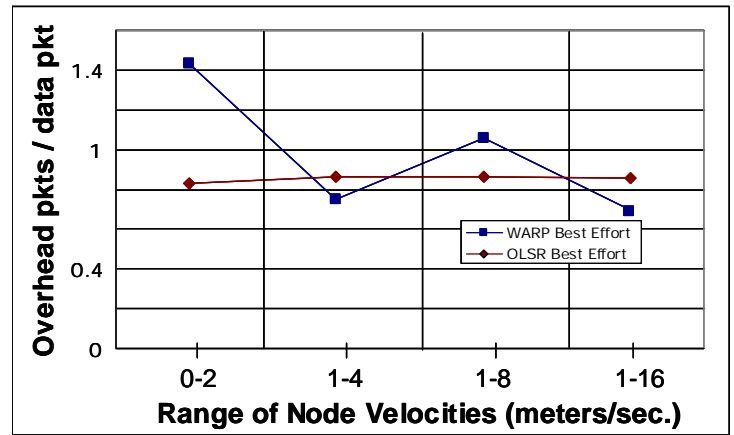


Figure 5. Routing Overhead for Random-Motion Case

For the clustered-motion case, this version of WARP did not adjust the zone-size – based on the relative fractions of PRP and RRP traffic – as recommended in [6]. As such, WARP's performance decreased as the probability ( $P_C$ ) of intra-cluster traffic became lower. For example, the poor performance for  $P_C = 0.2$  and Range of Node Velocities equal to [1-16] meters per sec was caused an increase in Route-Request messages without any decrease in the PRP/NDP traffic.

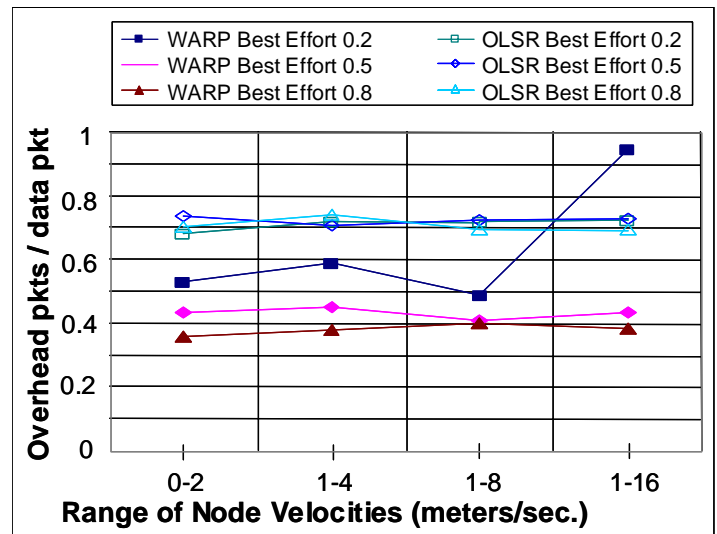


Figure 6. Routing Overhead for Clustered-Motion Case

### CONCLUSIONS AND RECOMMENDATIONS

The main conclusion is that hybrid routing protocols can be implemented as portable application-layer software

with reasonable complexity. The prototype-grade WARP software used in this paper is about 18,000 lines of code – of which about half is routing code and half is the overhead of the hybrid-routing framework and User Interface (UI).

The test-scenarios featured varying degrees of node mobility and non-uniform traffic patterns. The presented test results are an illustrative comparison of the benefits (and disadvantages) of hybrid routing. Additional experiments with working routing-software are ongoing. Future papers will also investigate QoS routing. The intended DoD applications for WARP include STRICOM's instrumented test-ranges, the Air Force's Cooperative Attack research, DARPA's Adaptive C4ISR Node (ACN) program and networks of unattended ground-based sensors.

## REFERENCES

- [1] T. Clausen, et al, "Optimized Link State Routing Protocol", draft-ietf-manet-olsr-06.txt, Sept. 1, 2001. (See: [www.ietf.org/html.charters/manet-charter.html](http://www.ietf.org/html.charters/manet-charter.html) for the latest versions of these Internet Drafts or subsequent RFCs.)
- [2] R. Ogier, et al, "Topology Broadcast Based on Reverse-Path Forwarding (TBRPF)", draft-ietf-manet-tbrpf-05.txt, March 1, 2002.
- [3] C. Santivanez and R. Ramanathan, "Hazy Sighted Link State Routing: A Scaleable Link State Algorithm", BBN Tech. Memo #1301, Aug. 31, 2001.
- [4] C. Perkins, et al, "Ad hoc On-Demand Distance Vector (AODV) Routing", draft-ietf-manet-aodv-10.txt, Jan. 19, 2002.
- [5] D. Johnson, "The Dynamic Source Routing Protocol for Mobile Ad Hoc Networks (DSR)", draft-ietf-manet-dsr-07.txt, Feb. 21, 2002.
- [6] Z. Haas and M. Pearlman, "Determining the Optimal Configuration for the Zone Routing Protocol", IEEE JSAC, Special Issue on Ad-Hoc Networks, August 1999.
- [7] C. Santivanez, "Asymptotic Behavior of Mobile Ad hoc Routing Protocols with respect to Traffic, Mobility and Size", Northeastern University CDSR Tech. Report TR-CDSR-00-52, Oct. 2000.