Cairo University/Massachusetts Institute of Technology

Technological Planning Program

# Bus Service Planning

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# CAIRO URBAN TRANSPORT PROJECT

FINAL REPORT

VOLUME II

## BUS SERVICE PLANNING

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Prepared by

M.I.T./Cairo University Team

# PREFACE

This report is one of a series of publications which describe various studies undertaken under the sponsorship of the Technology Adaptation Program at the Massachusetts Institute of Technology.

The United States Department of State, through the Agency for International Development, awarded the Massachusetts Insitute of Technology a contract to provide support at M.I.T. for the development, in conjunction with institutions in selected developing countries, of capabilities useful in the adaptation of technologies and problem-solving techniques to the needs of those countries. This particular study describes research conducted in conjunction with Cairo University, Cairo, Egypt.

In the process of making the TAP supported study some insight has been gained into how appropriate technologies can be identified and adapted to the needs of developing countries per se, and it is expected that the recommendations developed will serve as a guide to other developing countries for the solution of similar problems which may be encountered there.

This research is carried out by Cairo University/M.I.T. Technological Planning Program, under the auspices of the M.I.T. Technology Adaptation Program, which is funded by the United States Agency for International Development (USAID), Cairo, Egypt. The views and opinions expressed in this report, however, are those of the authors and do not necessarily reflect those of the sponsors.

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The report was prepared by Peter Furth and Nigel Wilson.

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# PREFACE

This is one of three companion reports summarizing the activities undertaken by this research team over the four year life of the project. The other two final reports are:

Volume I: Investment Planning and Project Programming

Volume III: Transport Planning Aids and Methods

Much of the early work on the project is described in Cairo Urban Transport Project Annual Report, December, 1979. There are also an extensive series of technical reports and theses produced during the project, which are referenced in this final report.

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# CHAPTER ONE

## INTRODUCTION

The urban transport system in Cairo is under increasing stress as the levels of population and auto ownership increase at a faster rate than the infrastructure which must accommodate the resulting demand. At the same time as street congestion is increasing, mass transit, provided principally in the form of buses operating in mixed traffic, must carry more people with an aging fleet which is unlikely to be increased significantly in the near future. While these problems are not unusual in the major cities of developing countries, Cairo suffers more than most in terms of narrow streets with severe traffic congestion and bus overcrowding.

In this report various strategies for improving the public transport system in Cairo are defined and analyzed. While many strategies could be developed encompassing all aspects of public transport system operation and management, given the constraints on time and effort existing, this report focuses on the operations planning and service design strategies. Thus other areas which might well prove as fertile, such as maintenance, bus replacement, and bus priority schemes will not be addressed here. The topic of operations planning was selected because it was felt to be possible to suggest new procedures, then test and implement them, all within the scope of this research. Stress was placed on developing planning methods which could be used by transit planners in Cairo directly without requiring additional data or computer assistance. This research has tackled one facet of the short range bus service problem in Cairo, and in no way satisfies the need for studying other facets of the short range public transport problem, let alone the need for longer term solutions.

## 1.1 The Cairo Urban Transport System

Cairo is situated about 170 km. from the Mediterranean Sea on the banks of the River Nile. The city itself had a 1979 population of 5.4 million with Greater Cairo, which includes parts of the neighboring governates of Giza and Kaliaubeau, having a population of 8.5 million, about 21% of the total population of Egypt. Due to the harsh terrain surrounding the city, population densities are extremely high, in the vicinity of 100,000 persons per square km. in several districts. Major industrial centers are located some 40 km. apart at each end of the principal north-south axis running along the Nile. Population growth is continuing at an annual rate of more than 5% currently.

Currently, the Cairo public transport system carries about four million passengers daily, a figure which has been increasing at an annual rate of six percent. The fleet consists of about 1500 operational buses, 150 (two-car) trams, 78 trolleys, and 15 ferries with service being provided on 250 bus lines, 27 tram lines, six trolley lines and five ferry lines. The ability of the transit system to meet this increasingly heavy demand is compromised by the existence of numerous problems.

First, the road network is strongly oriented toward the central city, imposing a radial orientation on the transit system as well. As the city has expanded, however, non-radial trip-making has become more important, resulting in severe congestion on the few existing crosstown streets and requiring that many transit trips be made with a transfer in the downtown area. Expansion of the roadway capacity would involve relocating large numbers of people which, given the chronic housing shortage in the city, is unacceptable. Second, the growth of the city within tight geographical

constraints has meant that most developable land is already used and there is little potential for major expansion of the road network. Furthermore, only a small percentage of city streets are designed and maintained to allow passage by buses, thus virtually every road on which a bus can possibly operate already has at least one bus line. As part of the radial structure there are three major transit terminals in the central city, and in many cases two different bus lines will operate on identical routes, but terminate at different transfer points. This overlapping route structure is the cause of some concern to transit planners in Cairo, suggesting that benefits might be derived from restructuring the network of routes. High population densities and low auto ownership levels have resulted in near-saturation levels of transit demand. The facts that 75% of all vehicular trips are by transit (the remainder are 19% auto and 6% taxi) and that the average productivity is 165 passenger trips per bus-hour indicate how heavily the system is used. Resource constraints, however, have severely limited the ability of the Cairo Transportation Authority (CTA), the primary agency responsible for the operation of public mass transportation facilities, to expand the system capacity.

The transportation planning process that exists in Cairo is not designed to address problems such as those identified above. In general, planning in Cairo has focused on long-range, large-scale projects. A preliminary master plan for the metropolitan area was prepared in 1970 in which secondary population centers served by an outer ring road were envisioned as the basic characteristic of the regional physical form. Within the city itself, a subway system is being constructed which will serve the major corridors. Even though this subway will help alleviate many of the transport problems in the city, it has been estimated that it

will serve only 30% of all trips. There are thus both short run needs and continuing needs for study of the components of the transport system to see where improvements can be made. The first step in this direction was taken with a 1978 system-wide transit origin-destination survey. This system-wide survey provides a useful data base for analyzing the effectiveness of the existing transit system.

## 1.2 General Approach

The focus adopted for this analysis was one of examining the existing operations of the transit system in Cairo. This focus was chosen for several reasons:

- There are no resources available to expand significantly the number of buses in the fleet.
- The transit network is so ubiquitous that efforts to expand the service are unnecessary.
- The proposed subway is designed to handle many of the trips in specific corridors. More efficient utilization of existing services in these corridors is thus meant as an interim strategy until the subway is constructed.

There were several factors that had to be considered in developing the analysis approach. Most importantly, the scale of analysis in this project would be much smaller than that traditionally used in Cairo. Whereas most previous efforts had focused on network or regionwide improvements, this analysis required a close look at individual transit lines. The type of information required for the analysis was thus very different from that previously used by planners in Cairo, thereby requiring efforts not only to develop technically sound analysis techniques, but

also to identify a strategy for explaining and demonstrating their use. Since a useful data base resulted from the onboard survey, initial efforts at developing analysis procedures relied heavily on this information. However, given the rapidly changing social and demographic characteristics of Cairo, it was recognized that this data base would quickly lose its value and, because of its cost, would unlikely be repeated for a long time. Thus, a set of analysis techniques are developed which rely on the continued monitoring of the transit system by the transit authority, thereby giving transit planners a tool which can be used to identify and evaluate prospective changes in the system as the urban environment itself changes.

Since the CTA bus system is a supply-constrained system and we are mainly concerned with changes that could be made in the short term, the potential change in demand caused by the modified operations are not considered in the analysis. For similar reasons, the effects of pricing and other means of influencing passenger choice are not considered.

In Cairo the overriding short-run planning objective must be to maximize the productivity of the vehicle fleet so that the greatest possible passenger carrying potential is achieved. To this end the analysis methods presented in this report are intended to restructure services to increase productivity within policy constraints on such things as maximum acceptable headways.

In order to keep this report brief, the procedures will be presented in summary form with detailed reports on each topic referenced in the Appendix. Similarly, applications of the methods in Cairo will be referred to, but not presented in detail.

The planning methods presented in this report can be characterized by the part of the system to which they apply. At the simplest level of a single bus line, the strategy of deadheading some of the buses in the lightly travelled direction will be analyzed. At the corridor level sets of interdependent routes can be analyzed both in terms of the structuring of each route, and the allocation of vehicles between routes. Routing strategies at this level include zonal, express, and local service. Finally, one can consider inter-corridor services such as through routes and crosstown services.

The remainder of this report summarizes the procedures which have been developed to investigate each strategy.

# CHAPTER TWO

## DEADHEADING

Deadheading, or running vehicles empty in the light direction of travel, can be an effective strategy for reducing operator costs during peak periods when there is a large imbalance in loads between the inbound and outbound directions of travel, and when the deadheading vehicles can use a faster path in the light direction than they would use if in service. On a route with a given number of vehicles, deadheading decreases the capacity available in the light direction (where capacity is least needed) while increasing the capacity available in the heavy direction, since deadheading vehicles can make their round trip faster and thus perform more heavy direction runs in a given period of time.

Two levels of deadheading can be employed on a route. If some trips deadhead while others serve passengers in the light direction, then this arrangement is called "partial deadheading." If all of the trips of a route deadhead, this arrangement is "complete deadheading." Complete deadheading can only be implemented on a route that belongs to a system of overlapping routes in which provision is made for light direction travelers to use a different route belonging to that system. Partial deadheading can be employed on isolated routes as well as on routes that belong to a system of overlapping routes. This chapter will cover partial deadheading on a single route, leaving complete deadheading to chapters 3 and 4 which deal with systems of overlapping routes.

## 2.1 Theory of Partial Deadheading

This section summarizes the theory relating to partial deadheading that is described in detail in Furth (1981). Let A denote the heavy direction of travel and B the light direction. Let $t_A$ be the run time in the heavy direction, $t_B$ the run time in the light direction in service, and $t_D$ the run time in the light direction when a vehicle is deadheading. These run times are defined as including the minimum layover. A partial deadheading configuration is characterized by a heavy direction service headway $h_A$ and a light direction service headway, $h_B$.

If no trips on a route deadhead in the light direction (i.e. $h_B = h_A$), the number of vehicles required, $N_c$, would be

$$N_c = \left\langle \frac{t_A + t_B}{h_A} \right\rangle \tag{2.1}$$

where $\langle x \rangle$ = the smallest integer greater than or equal to x. If every trip is deadheaded in the light direction ($h_B = \infty$), the number of vehicles needed, $n_A$, would be

$$n_A = \left\langle \frac{t_A + t_D}{h_A} \right\rangle \tag{2.2}$$

The partial deadheading solution will always require at least one vehicle more than $n_A$. Therefore, if $n_A \geq N_c - 1$, partial deadheading cannot reduce the number of vehicles needed on this route.

The vehicle savings possible on a route through partial deadheading depend on the "deadhead premium" on that route, which is $t_B - t_D$, the

difference in light direction run time between an in-service trip and a deadheading trip. But mixing deadhead trips with in-service trips on the same route may necessitate some extra layover for the deadheading trips, and so the "effective deadhead premium," $\pi$, lies between $(t_B - t_D)$ and $(t_B - t_D - h_A)$, since the deadheading trips will need an extra layover time of between 0 and $h_A$ minutes. The effective deadhead premium may be computed using the formula

$$\pi = t_A + t_B - h_A n_A \tag{2.3}$$

The ratio of the light direction service headway to the heavy direction service headway, $r = h_B/h_A$, is also a variable of interest. If no trips deadhead, then r=1; if half the trips deadhead, then r =2; in general, for a given r, the fraction of runs that deadhead is $\frac{r-1}{r}$. If r is an integer, the dispatching strategy is simple: the first of every r trips covers the light direction in-service, and the remaining (r-1) trips deadhead. If r is not an integer, the dispatching strategy becomes more complex. For example, in order to achieve a service headway ratio of r = 3.4 and space the light direction service departures at even headways, it would be necessary to dispatch the first, fourth, seventh, and fourteenth of every seventeen buses in-service and deadhead the remainder. In addition to requiring a complex dispatching strategy, a non-integer service headway ratio r also requires a longer layover on some of the runs in order to keep service departures evenly spaced. To help account for this extra layover, we introduce the function $g(r) = \frac{y-1}{y}$, where y is the smallest denominator of r when r is expressed as a ratio

of integers. If r is an integer, then r can be expressed as the fraction r/1, and thus g(r) = 0. If, for example, r = 3.4, then since $3.4 = \frac{17}{5}$, $g(r) = \frac{5-1}{5} = 0.8$.

The total number of vehicles required on a route using partial deadheading, assuming that the number of buses must be integer and that service departures in each direction must be even, may be expressed as the function $Np(h_A,r)$, which is given by

$$Np(h_A,r) = n_A + n_B$$

$$= \left\langle \frac{t_A + t_D}{h_A} \right\rangle + \left\langle \frac{\pi + g(r)h_A}{rh_A} \right\rangle \qquad (2.4)$$

where

$$n_B = \left\langle \frac{\pi + g(r)h_A}{rh_A} \right\rangle.$$

Because of the term g(r) in eq. (2.4), solutions with non-integer r have some built-in inefficiency. On a given route, solutions with an integer headway ratio r=k ($k \geq 2$) will often require less than or as many vehicles as solutions for which r is between k and k+1, even though the integer solution offers better service in the light direction. Under circumstances that would be expected in Cairo, integer headway ratio solutions were optimal (required the least number of vehicles under maximum service headway constraints) in over 90% of the cases examined. Because of this, and because integer solutions are so much easier to operate, we recommend that whenever partial deadheading is employed on a route, the light direction service headway should be an integer multiple of the heavy direction service headway. When the

service headway ratio is an integer, then the number of buses required on a route becomes

$$Np(h_A, r) = \left\langle \frac{t_A + t_D}{h_A} \right\rangle + \left\langle \frac{\pi}{rh_A} \right\rangle . \qquad (2.5)$$

## 2.2 Procedure for Applying Partial Deadheading in Cairo

In order for a route to qualify for partial deadheading, it must meet these two criteria:

a) Its light direction peak load is at most half as large as its heavy direction peak load.

b) Its heavy direction headway, $h_A$, which is sixty times the ratio of the bus capacity to the heavy direction peak load, must be no greater than half the policy headway (maximum headway allowed on a route).

If a route fails either of these tests, then any partial deadheading configuration would either overcrowd the light direction trips or provide light direction service that is too infrequent.

Furthermore, a candidate route must also have a path for deadheading that takes at least $h_A$ fewer minutes than an in-service trip in the light direction; that is, we require that $t_D < t_B - h_A$.

If a route meets these three tests, it is a candidate for partial deadheading. Its maximum light direction service headway, $h_B^{max}$, is sixty times the bus capacity divided by the light direction peak load. The maximum service headway ratio is then $r^{max} = \text{Int}\left[\frac{h_B^{max}}{h_A}\right]$, where Int [x] is the integer portion of x. The service headway ratio could then be any integer $2, \ldots, h_B^{max}$. We recommend that every possible value of r be tried; the planner can then choose the preferred value. As r gets

smaller, the service level in the light direction improves, but the number of vehicles needed may increase.

A manual worksheet for executing this procedure for a given route in a given time period is displayed in Exhibit 2.1. Necessary data inputs are policy headway, vehicle capacity, peak load in each direction, and trip times. Note that trip times should include minimum layover at the end of the trip. It is also important that the policy headway and the vehicle capacities be realistic and reflect the operator's vehicle resources. For example the CTA considers that the capacity of a vehicle is 80 persons and that headways should be no longer than 10 minutes; but with the current (and, it seems, perpetual) vehicle shortage in Cairo, these standards cannot be attained. To impose such high standards on one route when most other routes in the system violate these standards is inappropriate. The standards used should be realistic; that is, there should be very few routes whose mean peak load in the peak period exceeds the standard capacity, and very few routes with headways exceeding the policy headway. For the current level of resources at the CTA, a capacity of 120 or 130 passengers and a policy headway of 20 minutes are probably appropriate.

## 2.3 Example

Route 57 has the following parameters in the weekday morning peak:

minimum layover = 25% of run time for in-service trips, 12% of run time for deadheading trips

trip time inbound = 34 min $\rightarrow t_A = 34 \cdot 1.25 = 42.5$ min.

trip time outbound = 32 min $\rightarrow t_B = 32 \cdot 1.25 = 40.0$ min.

trip time deadheading = 14 min $\rightarrow t_D = 14 \cdot 1.12 = 15.7$ min.

peak load inbound = 575 pax/hr

peak load outbound = 220 pax/hr

bus capacity (including standees) = 63 pax

policy headway = 30 min.

Exhibit 2.2 is the Partial Deadheading Worksheet with the Route 57 example executed on it. The number of buses needed throughout deadheading, shown in Step 4, is $N_c = 13$. Only one deadheading configuration with an integer service headway ratio r is feasible; for this configuration (r=2), 11 buses are needed (Step 9). Therefore, the optimal deadheading configuration (Step 10) has an inbound headway of 6.5 minutes and an outbound service headway of 13 minutes. Two buses are saved then, as half the remaining vehicles deadhead under the new service configuration.

## Exhibit 2.1

## Partial Deadheading Worksheet

Route: _____ Date: _____

Time Period: _____ Bus Capacity C = _____ pax/veh

Policy Headway H = _____ min

| Heavy Direction | Light Direction |
|---|---|
| Peak load $L_1$ = _____ pax/hr | Peak load $L_2$ = _____ pax/hr |
| Headway $h_A = 60C/L_1$ = _____ min | Max headway $h_B^{max} = \min[60C/L_2, H]$ = _____ min |
| Trip time $t_A$ = _____ min | Trip time $t_B$ = _____ min |
| | Trip time deadheading $t_D$ = _____ min |

1. $r^{max} = \mathrm{Int}[h_B^{max}/h_A]$ = _____. If $r^{max} < 2$, check ☐ and STOP.
2. If $h_A > H/2$, check ☐ and STOP.
3. If $t_D + h_A \geq t_B$, check ☐ and STOP.
4. $N_c = \left\langle \frac{t_A + t_B}{h_A} \right\rangle$ = _____.
5. $n_A = \left\langle \frac{t_A + t_D}{h_A} \right\rangle$ = _____. If $n_A \geq N_c - 1$, check ☐ and STOP.
6. $\pi = t_A + t_B - h_A n_A$ = _____.
7. Let $r = r^{max}$ = _____.
8. $Np(r) = n_A + \left\langle \frac{\pi}{r h_A} \right\rangle$ = _____. If $Np(r) \geq N_c$, check ☐ and STOP.

If any box was checked in Steps 1-8, no vehicles can be saved through partial deadheading.

Exhibit 2.1 (cont'd)

9. Let $r = r^{max}$, $r^{max} - 1$, $r^{max} - 2$, ..., 2. For each value of r compute Np(r).

a. $r = r^{max} =$ _____ $h_B = rh_A =$ _____ $Np = n_A + \left\langle \frac{\pi}{h_B} \right\rangle =$ ____ 1/ 2/

b. $r = r^{max} - 1 =$ _____ $h_B = rh_A =$ _____ $Np = n_A + \left\langle \frac{\pi}{h_B} \right\rangle =$ _____ 2/

c. $r = r^{max} - 2 =$ _____ $h_B = rh_A =$ _____ $Np = n_A + \left\langle \frac{\pi}{h_B} \right\rangle =$ _____ 2/

d. $r = r^{max} - 3 =$ _____ $h_B = rh_A =$ _____ $N_p = n_A + \left\langle \frac{\pi}{h_B} \right\rangle =$ _____ 2/

Note 1/: this was already computed in Step 8.

Note 2/: if r = 2, or if $Np(r) = N_c$, STOP.

10. All of the solutions in Step 9 for which $Np(r) < N_c$ are potential solutions. Choose one taking into account the light direction level of service as well as the number of vehicles required.

Chosen solution: $h_A =$ _____ min

$h_B =$ _____ min

$N_p =$ _____ buses

## Exhibit 2.2

## Partial Deadheading Worksheet

Route: 57

Date: _____

Time Period: 1

Bus Capacity $C$ = 63 pax/veh

Policy Headway $H$ = 30 min

### Heavy Direction

Peak load $L_1$ = 575 pax/hr

Headway $h_A = 60C/L_1$ = 6.5 min

Trip time $t_A$ = 42.5 min

### Light Direction

Peak load $L_2$ = 220 pax/hr

Max headway $h_B^{max} = \min[60C/L_2, H]$ = 17.5 min

Trip time $t_B$ = 40.0 min

Trip time deadheading $t_D$ = 15.7 min

1. $r^{max} = \mathrm{Int}[h_B^{max}/h_A]$ = 2. If $r^{max} < 2$, check ☐ and STOP.
2. If $h_A > H/2$, check ☐ and STOP.
3. If $t_D + h_A \geq t_B$, check ☐ and STOP.
4. $N_c = \left\langle \frac{t_A + t_B}{h_A} \right\rangle$ = 13.
5. $n_A = \left\langle \frac{t_A + t_D}{h_A} \right\rangle$ = 9. If $n_A \geq N_c - 1$, check ☐ and STOP.
6. $w = t_A + t_B - h_A n_A$ = 24.
7. Let $r = r^{max}$ = 2.
8. $Np(r) = n_A + \left\langle \frac{\pi}{r h_A} \right\rangle$ = 11. If $Np(r) \geq N_c$, check ☐ and STOP.

If any box was checked in Steps 1-8, no vehicles can be saved through partial deadheading.

Exhibit 2.2 (cont'd)

9. Let $r = r^{max}$, $r^{max} - 1$, $r^{max} - 2$, ..., 2. For each value of r compute Np(r).

a. $r = r^{max} =$ 2 $h_B = rh_A =$ 13 $Np = n_A + \left\langle \frac{\pi}{h_B} \right\rangle =$ 11 1/ 2/

b. $r = r^{max} - 1 =$ _____ $h_B = rh_A =$ _____ $Np = n_A + \left\langle \frac{\pi}{h_B} \right\rangle =$ _____ 2/

c. $r = r^{max} - 2 =$ _____ $h_B = rh_A =$ _____ $Np = n_A + \left\langle \frac{\pi}{h_B} \right\rangle =$ _____ 2/

d. $r = r^{max} - 3 =$ _____ $h_B = rh_A =$ _____ $N_p = n_A + \left\langle \frac{\pi}{h_B} \right\rangle =$ _____ 2/

Note 1/: this was already computed in Step 8.

Note 2/: if r = 2, or if $Np(r) = N_c$, STOP.

10. All of the solutions in Step 9 for which $Np(r) < N_c$ are potential solutions. Choose one taking into account the light direction level of service as well as the number of vehicles required.

Chosen solution: $h_A =$ 6.5 min

$h_B =$ 13 min

$N_p =$ 11 buses

# CHAPTER THREE

## LOCAL ZONAL SERVICE WITH EXCLUSIVE BOARDING AND ALIGHTING ZONES

Local zonal service with exclusive boarding and alighting zones can be an efficient means of providing bus service in single arterial corridors having high demand which is heavily oriented toward the downtown. This routing strategy includes a number of routes, each of which begins at a different uptown terminal; these terminals are staged along the corridor at increasing distances from downtown. Each route operates between its terminal and the downtown terminal. Inbound a route picks up passengers only within its boarding zone; after the end of its boarding zone, it continues traveling along the arterial, stopping to discharge passengers where they desire to alight, but not picking up any more passengers. Outbound a route may pick up passengers at any stop between downtown and its uptown terminal, but it may discharge passengers only in its alighting zone. It is also possible that a route may deadhead, and therefore have no alighting zone outbound in the morning peak or no boarding zone inbound in the evening peak.

The boarding zone of an active route that does not deadhead inbound extends from its uptown terminal to the next inner terminal out of which a route operates that does not deadhead inbound. That is, if terminals are numbered consecutively and terminal 1 is the outermost terminal in the corridor, the boarding zone of route 1 (the route beginning at terminal 1) will be the segment between terminal 1 and terminal 2 if route 2 is active and does not deadhead inbound; however, if route 2 is inactive or if it deadheads inbound, then route one's boarding zone has to include

the segment between terminal 2 and terminal 3 as well. Analogously, the alighting zone of an active route that does not deadhead outbound is the segment between its uptown terminal and the next inner terminal that has an active route that does not deadhead outbound.

A zonal configuration designed for an off-peak period (in which loads inbound and outbound are similar) will not include any deadheading routes. Then a route's boarding zone will be the same as its alighting zone. If we are designing for a peak period, we may want to let some routes deadhead in the light direction. Then the design becomes more complex, since active routes may deadhead or not deadhead, and as a result a route's alighting zone may differ from its boarding zone. In either peak or off-peak periods, we may choose to let a route be active or inactive (i.e. not operate at all .

Two different procedures will be presented, one for design of off-peak zonal service, and the other for design of peak period zonal service. The off-peak procedure is simpler since it prohibits deadheading. These procedures find the zonal service routing configuration, and the service headway for each component route, that minimizes the cost of operating the set of routes. For the remainder of this chapter we assume that cost is proportional to the number of vehicles required, and therefore we minimize the number of vehicles required. One may choose instead to minimize a weighted sum of operating cost, wait time cost, in-vehicle time cost, etc. In this case where we compute the number of vehicles required on a route, the cost of that route should be computed in terms of the specified function to be minimized.

## 3.1 Design for Off-Peak Periods

The following notation is used:

$n$ = number of potential uptown terminals. Terminals should be numbered consecutively, with terminal 1 being the outermost terminal in the corridor and terminal n the innermost. Let the downtown terminal be indexed n+1.

route $(j,k)$ = route whose boarding zone and alighting zone extends from terminal j to the stop just before terminal k+1 ($k \geq j$).

$B_{jk}$ = minimum number of buses needed to serve route $(j,k)$

$Z_{jk}$ = minimum number of buses needed to serve inbound demands originating beyond terminal k+1 and outbound demands terminating beyond terminal k+1 when only routes beginning at terminals 1,...,j are allowed to be active.

In a corridor with n potential uptown terminals, there are $n(n+1)/2$ potential routes. The first step in the design is to compute the number of buses needed by each potential route $(j,k)$, $j=1,\ldots,n$ and $k=j,\ldots,n$. To compute the number of vehicles needed on a route, one needs to know that route's peak load and its trip time. If its peak load is $L_{jk}$ (pax/hr), its trip time (including layover) is $T_{jk}$ (min), the bus capacity is C (pax/veh), and the policy (maximum allowable) headway is H, the minimum headway of route $(j,k)$ will be

$$h'_{jk} = \min \left\{ H, \frac{60C}{L_{jk}} \right\} \tag{3.1}$$

and the number of vehicles needed will be

$$B_{jk} = \left\langle \frac{T_{jk}}{h'_{jk}} \right\rangle$$

where < > means round up to the next higher integer.

It is necessary then to estimate the trip time $T_{jk}$ and peak load $L_{jk}$ for every potential route. Methods for estimating these quantities will not be presented here, as a route planner will certainly be familiar with methods to estimate peak loads and trip times given a route's alignment and its boarding and alighting zones. Peak loads, trip times, and resulting minimum headways and vehicular requirements should be recorded in matrices that have the form of the matrix shown in Exhibit 3.1; that is, there should be one matrix $[(L_{jk})]$ for peak loads, one matrix $[(T_{jk})]$ for trip times, etc.

Once the matrix of vehicles required $[(B_{jk})]$ is completed, we may begin to fill in another matrix, the matrix of values of $Z_{jk}$. This matrix is displayed in Exhibit 3.2. The first row of this matrix should be simply copied from the first row of the matrix of $B_{jk}$. Fill in the second row next, then the third, and so forth. Within a row, fill in the cells from left to right, beginning with the cell that is on the diagonal. The cells in the second and subsequent rows require two entries. In the small box of cell (j,k), enter the sum $(B_{jk} + Z_{j-1,j-1})$. Notice that $Z_{j-1,j-1}$ will be the diagonal entry of the next row up. Then in the larger part of cell (j,k), enter either the value in the small box of that cell or the value in the cell just above cell (j,k) (i.e. $Z_{j-1,k}$), whichever is smaller. In this step we are performing the computation $Z_{jk} = \min \{B_{jk} + Z_{j-1,j-1}, Z_{j-1,k}\}$. If the value chosen was $Z_{j-1,k}$ or if there was a tie (i.e. $Z_{j-1,k} \leq B_{jk} + Z_{j-1,j-1}$), put an X through the small box in the cell. (Therefore, whenever the value in the small box is greater than or equal to the value in the cell, there should be an X through the small box.)

## Exhibit 3.1

## Matrix for Recording Route Performance

Contents ($C_{jk}$) where contents could be peak load ($L_{jk}$), or trip time ($T_{jk}$), or minimum headway ($h'_{jk}$), or vehicles required ($B_{jk}$).

| j \ k | 1 | 2 | 3 | 4 | ... | n |
|---|---|---|---|---|---|---|
| 1 | $C_{11}$ | $C_{12}$ | $C_{13}$ | $C_{14}$ | ... | $C_{1n}$ |
| 2 | | $C_{22}$ | $C_{23}$ | $C_{24}$ | ... | $C_{2n}$ |
| 3 | | | $C_{33}$ | $C_{34}$ | ... | $C_{3n}$ |
| 4 | | | | $C_{44}$ | ... | $C_{4n}$ |
| ... | | | | | ... | ⋮ |
| n | | | | | | $C_{nn}$ |

j = first terminal in boarding/alighting zone

k = 1 terminal in boarding/alighting zone

Exhibit 3.2

Matrix for Recording $Z_{jk}$

| j \ k | 1 | 2 | 3 | ... | n |
|---|---|---|---|---|---|
| 1 | $Z_{11}$ | $Z_{12}$ | $Z_{13}$ | ... | $Z_{1n}$ |
| 2 | | $Z_{22}$ | $Z_{23}$ | ... | $Z_{2n}$ |
| 3 | | | $Z_{33}$ | ... | $Z_{3n}$ |
| ⋮ | | | | ⋱ | ⋮ |
| n | | | | | $Z_{nn}$ |

Once the matrix $[(Z_{jk})]$ is filled in, the active routes that make up the optimal routing configuration can be found. Begin at the bottom right cell of the matrix $[(Z_{jk})]$, i.e. cell (n,n). If there is an X through the small box in that cell, then the route corresponding to that cell is inactive; if there is no X, that route is active. If that cell's route is inactive, go to the next higher cell and repeat the procedure. If that route is also inactive, keep going up until an active route is found, record its address (j,k), and go to the diagonal cell of the next row up (i.e. row j-1) and begin the search again. Continue this procedure until you arrive at the top row (any top row cell you reach has an active route).

Having recorded the active routes in the optimal routing configuration, simply read the number of vehicles required by any route (j,k) from the matrix $[(B_{jk})]$. The headway $h_{jk}$ of an active route (j,k) can then be computed as

$$h_{jk} = \min \{H, \frac{T_{jk}}{B_{jk}}\} \tag{3.3}$$

## 3.2 Example of Off-Peak Design

A single arterial corridor has four potential uptown terminals. A study of passenger movements and vehicle trip times along the arterial have led to the matrices of peak loads and run times for each of the $4 \cdot 5 \div 2 = 10$ potential routes. These matrices, $[(L_{jk})]$ and $[(T_{jk})]$, are displayed in Exhibit 3.3.

The policy headway is 20 minutes and the bus capacity is 50 passengers. Using equations (3.1) and (3.2), the matrices $[(h'_{jk})]$ and $[(B_{jk})]$ are computed as shown in Exhibit 3.4.

## Exhibit 3.3

## Example Matrices of Peak Load and Trip Time

Peak Load of Route (j,k) ($L_{jk}$) (pax/hr)

| j \ k | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| 1 | 200 | 350 | 450 | 600 |
| 2 | | 160 | 270 | 430 |
| 3 | | | 120 | 290 |
| 4 | | | | 190 |

Trip Time of Route (j,k) ($T_{jk}$) (min)

| j \ k | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| 1 | 90 | 95 | 100 | 105 |
| 2 | | 70 | 75 | 80 |
| 3 | | | 55 | 60 |
| 4 | | | | 45 |

## Exhibit 3.4

### Example Matrices of Headway and Vehicles Required

Minimum Headway of Route (j,k) (min)

$$h_{jk} = \min \{20, \frac{60 \cdot 50}{L_{jk}}\}$$

| j \ k | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| 1 | 15.0 | 8.6 | 6.7 | 5.0 |
| 2 | | 18.8 | 11.1 | 7.0 |
| 3 | | | 20.0 | 10.3 |
| 4 | | | | 15.9 |

Vehicles Required by Route (j,k)

$$B_{jk} = \langle \frac{T_{jk}}{h'_{jk}} \rangle$$

| j \ k | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| 1 | 6 | 11 | 15 | 21 |
| 2 | | 4 | 7 | 12 |
| 3 | | | 3 | 6 |
| 4 | | | | 3 |

The matrix $[(Z_{jk})]$ is then completed in Exhibit 3.5. Also shown in Exhibit 3.5 is the path of the search for the routes belonging to the optimal configuration. As shown in Exhibit 3.5, there are 3 routes in the optimal configuration: routes (3,4), (2,2), and (1,1). Matrix $[(B_{jk})]$ shows that these routes need 6, 4, and 6 buses respectively, for a total of 16 buses (compared with 21 buses for the conventional single local route (1,4)).

The headways of the optimal routes are found using equation (3.3):

$$h_{3,4} = \frac{60}{6} = 10 \text{ min}$$

$$h_{2,2} = \frac{70}{4} = 17.5 \text{ min}$$

$$h_{1,1} = \frac{90}{6} = 15 \text{ min.}$$

## 3.3 Design for Peak Periods

The design of zonal routes for peak periods is more complex, because loads are not only heavier toward the downtown end of the route but also are imbalanced by direction (i.e., the loads in one direction are far greater than those in the other direction). This load imbalance suggests that some of the zonal routes deadhead.

Potential uptown terminals should be numbered just as described in Section 3.1. The remainder of this discussion will assume that we are dealing with the morning peak, when the traffic is heavier in the inbound direction. Design for the evening peak is essentially the same, requiring a few reversals in definition. Let segment j be the road segment between terminal j and the stop just before terminal j+1. Then let:

## Exhibit 3.5

### Example Matrix $[(Z_{jk})]$

$Z_{jk}$

| j \ k | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| 1 | 6 | 11 | 15 | 21 |
| 2 | | 4+6=10<br>10 | 7+6=13<br>13 | 12+6=18<br>18 |
| 3 | | | 3+10=13<br>13 | 6+10=16<br>16 |
| 4 | | | | 3+13=16<br>16 |

Tracing the Optimal Configuration:

| j \ k | 1 | 2 | 3 | 4 | Optimal Routes |
|---|---|---|---|---|---|
| 1 | 0 | | | | (1,1) |
| 2 | | 0 | | | (2,2) |
| 3 | | | | 0 | (3,4) |
| 4 | | | | | |

route (j,k,g) = route whose uptown terminal is j, whose inbound boarding zone includes segment j through segment k, and whose outbound alighting zone includes segment g through segment j. Employ the convention that if g = 0, the route deadheads outbound. Route (j,k,g) is a valid route only if $k \geq j$ and if $g = 0$ or $g \geq k$.

$T_{jkg}$ = trip time (round trip, including layover) on route (j,k,g) (min)

$B_{jkg}$ = minimum number of buses needed to serve route (j,k,g).

$h_{jkg}$ = maximum headway on route (j,k,g) (min)

$L_{jkg}$ = peak load on route (j,k,g) (pax/hr)

$Z_{kg}$ = minimum number of buses needed to serve inbound demands originating on segments 1,...,k and outbound demands destined for segments 1,...,g. ($Z_{kg}$ is computed at different values of j; at a given value of j, routes may begin at terminals 1,...,j only).

First, all of the potential routes in the system must be analyzed. For each route the inbound and outbound trip times and peak loads inbound must be computed. Note that many of these figures will not differ between a number of routes; for example, route (1,4,4) will have the same inbound trip time and peak load as route (1,4,5). To record the total round trip time and peak load (maximum of inbound and outbound peak load) of a route, a number of matrices are needed. One can record the peak loads $L_{jkg}$ of routes (j,k,g) in a series of matrices $((L_{1kg}))$, $((L_{2kg}))$, etc., as illustrated in Exhibit 3.6. The values of $L_{1kg}$ (i.e. all of the $L_{jkg}$ for j=1) can be put into an $n \times n$ matrix; the values of $L_{2kg}$ into an $(n-1) \times n$ matrix, and so forth. (An extra column in the second and subsequent matrices is necessary to record deadheading routes). Similarly, the run times $T_{jkg}$ of each route can be recorded in a series of matrices.

## Exhibit 3.6

### Matrices for Recording $L_{jkg}$, $T_{jkg}$, $h'_{jkg}$, and $B_{jkg}$

For illustration's sake, assume n=4, and that we are recording $L_{jkg}$.

$((L_{1kg}))$ (i.e. j=1)

| k \ g | 1 | 2 | 3 | 4 | * |
|---|---|---|---|---|---|
| 1 | $L_{111}$ | $L_{112}$ | $L_{113}$ | $L_{114}$ | |
| 2 | | $L_{122}$ | $L_{123}$ | $L_{124}$ | |
| 3 | | | etc. | | |
| 4 | | | | | |

$(L_{3kg}))$ (i.e. j=3)

| k \ g | 3 | 4 | 0 |
|---|---|---|---|
| 3 | $L_{333}$ | $L_{334}$ | $L_{330}$ |
| 4 | | $L_{344}$ | $L_{340}$ |

$((L_{2kg}))$ (i.e. j=2)

| k \ g | 2 | 3 | 4 | 0 |
|---|---|---|---|---|
| 2 | $L_{222}$ | $L_{223}$ | $L_{224}$ | $L_{220}$ |
| 3 | | $L_{233}$ | $L_{234}$ | $L_{230}$ |
| 4 | | | etc. | |

$((L_{4kg}))$ (i.e. j=4)

| k \ g | 4 | 0 |
|---|---|---|
| 4 | $L_{444}$ | $L_{440}$ |

*The first matrix has no column zero since routes beginning at terminal 1 may not deadhead.

Then the headways of each potential route can be computed and recorded in a third series of matrices. To compute the maximum headways, use the formula (analogous to (3.1))

$$h'_{jkg} = \min \{H, \frac{60C}{L_{jkg}}\} . \tag{3.4}$$

Finally, fill in a fourth series of matrices with entries $B_{jkg}$, computed using the formula (analogous to (3.2))

$$B_{jkg} = \frac{T_{jkg}}{h'_{jkg}} . \tag{3.5}$$

Once the values of $B_{jkg}$ are recorded, we can execute a dynamic program to find the routing configuration that requires the least number of buses. To execute this three-dimensional problem on a two-dimensional piece of paper requires using the worksheet illustrated in Exhibit 3.7 and using a pencil (to allow erasing). The worksheet is a matrix whose rows correspond to values of k and whose columns correspond to values of g. This matrix has the same dimensions as the matrix $[(B_{1jk})]$. Then perform the following steps.

1. Copy the entries of the matrix $((B_{1kg}))$ into the main part of each corresponding cell (k,g) on the worksheet. Each cell (k,g) on the worksheet now contains a value of $Z_{kg} = B_{1kg}$. In the corner box of each cell, enter the number "1".

2. Draw a heavy line between rows 1 and 2 on the worksheet, since row 1 will remain untouched. Let j = 2.

3. Take out the matrix $((B_{jkg}))$ (e.g. when j=2, take out matrix $((B_{2kg}))$).

Exhibit 3.7

Worksheet for Peak Period Zonal Route Design

(For illustration, assume n=4)

$((Z_{kg}))$

| k \ g | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| 1 | $Z_{11}$ | $Z_{12}$ | etc. | |
| 2 | | | | |
| 3 | | | | |
| 4 | | | | |

4. For each cell (k,g) of the worksheet that is below the lowest heavy line, perform the following steps:

   a. Add the entry in the corresponding cell of matrix $((B_{jkg}))$ (i.e. cell (k,g)) to the diagonal cell on the worksheet that is just above the lowest heavy line (i.e. cell (j-1, j-1)). If this sum is less than the current entry in cell (k,g) of the worksheet, replace the contents of the corner box of cell (k,g) with the number j. (E.g. if j=2 and we are dealing with cell (3,4), read $B_{234}$ from cell (3,4) of matrix $((B_{2kg}))$, read $Z_{11}$ from cell (1,1) of the worksheet, and sum them. Compare this sum with $Z_{34}$. If this sum is greater than $Z_{34}$, go to Step 4b. Otherwise, erase the contents of the worksheet's cell (3,4), enter the sum in the main part of the cell, and write "2" in the corner of the cell.)

   b. From matrix $((B_{jkg}))$, read the entry in the last column (column 0) of row k and add it to the entry on the worksheet in the row just above the heavy line in column g. If this sum is less than the current entry in cell (k,g) of the worksheet, replace the current entry in (k,g) with this sum, and replace the contents of the corner box of that cell with the number j followed by the letter "d" (for "deadheading"). (i.e., for cell (3,4) when j=2, read $B_{230}$ from the last column of row 3 in matrix $((B_{2kg}))$, read $Z_{14}$ from column 4 of the row 1 of the worksheet (the row just above the lowest heavy line), and sum them. If this sum is greater than or equal to the worksheet's current entry in cell (3,4), nothing more in this step. Otherwise, erase the entire contents of cell (3,4) of the worksheet replacing the main entry with the sum just computed and putting "2d" in the corner box.)
   Note: Perform Steps 4a and 4b for every cell of the worksheet below the lowest heavy line.

5. If j=n, go to Step 6. Otherwise, draw a heavy line under row j of the worksheet. Put away matrix $((B_{jkg}))$. Let j = j+1. Go to Step 3.

6. The optimal solution has now been found, but it must be traced. Begin at the bottom right cell of the worksheet, cell (n,n). The entry in this cell, $Z_{nn}$, indicates the total number of buses required. Let k=g=n.

7. Let j equal the number in the corner box of the cell we are now looking at (i.e. cell (k,g)).

   a. If the corner box contains the letter "d" as well as the number j, then route (j,k,0) is active. Record this. Then ~~trace~~d up in worksheet, ~~remaining~~ in column g, to row (j-1). Now let k = j-1, and go to Step 7.

b. If the corner box does not contain the letter "d", then route (j,k,g) is active. Record this. If j=1, go to Step 8. Otherwise, go to the diagonal cell of row (j-1). Let k=g=j-1. Go to Step 7.

8. The active routes belonging to the optimal solution were recorded in Step 7. The number of buses required by each route (j,k,g), $B_{jkg}$, can be read from cell (k,g) of matrix $((B_{jkg}))$. The run time, $T_{jkg}$, can be read from cell (k,g) of matrix $((T_{jkg}))$. The best headway for route (j,k,g) should then be computed and recorded:

$$h_{jkg} = \min\{H, \frac{T_{jkg}}{B_{jkg}}\} \qquad (3.6)$$

Because the above procedure requires erasing and replacing worksheet entries, it is difficult to illustrate, so no example is provided. However, the reader is encouraged to work through an example, after working through the example of Section 3.2, as this will certainly enhance understanding the procedure.

# CHAPTER FOUR

## ROUTES WITH OVERLAPPING SERVICE ZONES

A common routing configuration existing in Cairo is overlapping routes. It is not uncommon for a long road segment to have three or more routes covering its entire length. These routes have no explicit boarding or alighting restrictions; hence such a route's boarding and alighting zones may be considered to extend the entire length of the route, and the boarding and alighting zones of overlapping routes therefore overlap. To the passenger, overlapping service zones mean a choice of which route to use. This choice makes analysis of an overlapping zone route system difficult, since it makes it necessary to predict the number of riders using each of the overlapping routes. This prediction requires some understanding of both passenger behavior and the operating characteristics of an overlapping route system.

Overlapping routes exist for three major reasons. The first is that a corridor may have numerous uptown branches. If a route begins at the extreme point of each of those branches, then all of those routes will overlap along the length of the trunk. Secondly, a corridor may serve more than one downtown terminal. To provide direct service in a corridor to all the downtown terminals, the routes must overlap within the corridor. Thirdly, short routes that are entirely overlapped by longer routes can be a more economical way of serving large volumes of short trips rather than having the short-distance travelers use a more costly longer route.

Designing routes with overlapping zones has three parts. First, one must choose the routing configuration; second, one must predict which route each passenger will use; third, one must allocate buses to

each route so as to serve its passengers. These last two parts are interdeperdent, since the number of buses allocated to a route determines the service frequency, which affects passenger path choice. Thus, the design process is broken into two stages. One stage is passenger path assignment and bus allocation, discussed in Sections 4.1 to 4.4; the second stage, route configuration, is discussed in Section 4.5.

One can view overlapping route system design from two points of view: a system-optimizing point of view that dictates passenger route choice so as to minimize total system cost, and a user-optimizing point of view that allows a passenger to select the path that best serves him. These two points of view correspond to Wardrop's two principles of traffic assignment [Wardrop]. Since in real life passengers are free to select the route they prefer in an overlapping route system, the user-optimized point of view is usually the correct one for system design; nevertheless, the system-optimized point of view is worth studying, for although the transit operator cannot dictate path choice to the users, it can use incentives to influence path choice, and the system-optimized solution gives the operator a target toward which he can aim his incentives.

## 4.1 Passenger Route Choice

There are many factors that can influence passenger route choice, each with differing degrees of importance. In a corridor in Cairo, route choice is unlikely to be affected by differences in in-vehicle time, so that the major factors affecting route choice are number of transfers and fare. For poorer travelers, fare is a more important factor; for less poor travelers, number of transfers is more influential. Also when the

trip in the corridor will be followed by a transfer to another line, passengers prefer to transfer at the terminal of the second route, if possible, in order to increase their chances of finding a seat on the bus, otherwise they prefer to stay on the first bus they board as long as possible.

Using the above criteria, the set of acceptable paths that a group of passengers of a given income class traveling from one point to another will use can be narrowed. For poorer passengers, the criteria that determine an acceptable path, in order of decreasing importance, are:

1. Eliminate paths that are not minimum price (i.e. fare) paths
2. Eliminate paths that are not minimum transfer paths
3. If a transfer must occur and it is possible to make it at the terminal of the route to which the passengers are transferring, eliminate all paths that entail transfers at points that are not terminals.
4. When a transfer can be made at different points along a route, eliminate all paths except those that entail transferring at the last possible stop.

For less poor travelers, simply reverse the ranking of the first two criteria. Often the set of paths acceptable to poor and less poor will be identical since in Cairo one pays an extra fare with each transfer, making the minimum transfer path the minimum price path.

If by applying the above criteria it is found that a particular origin-destination (O-D) pair and income class combination has only one acceptable path, then passengers of that income class traveling from that origin to that destination are called "captive flow;" if more than one acceptable path exists, those passengers are "variable flow." Assigning captive flow to their path is straightforward, since they have only one acceptable path. Assigning the variable flow to a route or distributing

it among a set of routes is more difficult, since it is not clear how it will, in fact, distribute itself. It is the problem of assigning these variable flows that makes it difficult to plan service on overlapping routes.

## 4.2 System-Optimized Passenger Assignment and Bus Allocation

As mentioned before, one can take two viewpoints in designing overlapping routes. One viewpoint says, "Let everyone choose their preferred path and design the system around the resulting flows to minimize cost;" the other says, "Let us determine where the people with a choice of path should go and then design the system so that the resulting total cost will be minimized." This second view, the system-optimized criteria, is discussed in this section.

To minimize total operator cost in a system of overlapping routes, we should assign the variable flows in such a way that peak loads on the longer routes are as small as possible, preferring instead to load the shorter, cheaper routes. The following algorithm may be used to assign passenger flows and allocate vehicles to minimize systemwide operator cost.

### Algorithm 4.1

1. Construct a load profile of the corridor. Note the area where the load is within 150 pax/hr of the peak load. Call this the "peak load area."

2. Assign all captive flows to their unique paths.

3. Identify the peak load of each route as now loaded. If a route's peak load is small, one should consider eliminating that route unless it is shorter than routes that overlap it.

4. Rank variable flows by length, beginning with the longest. If a variable flow does not cross the peak load area, exclude it from the ranking.

5. Beginning with the longest variable flow and progressing according to the ranking of Step 4, assign variable flows using the following rules:

   a. If any or all of the variable flow can be assigned to a route without increasing its peak load, assign it to that route.

   b. If any or all cannot be assigned as in Step 5a, assign it to the acceptable path route with the shortest run time.

6. The number of vehicles that should be allocated to each route is then

$$n_i = \frac{t_i L_i}{60C}$$

where $n_i$ = number of buses allocated to line i

$t_i$ = round trip time on route i (min)

$C$ = bus capacity (pax/bus)

$L_i$ = peak load on route i (pax/hr)

If integer vehicle allocation is desired, round $n_i$ to the nearest integer.

The service headway on route i will then be $t_i/n_i$. Note that the simplest consistent way to apply capacity constraints in Cairo's overcrowded bus system is to set C equal to the average peak load on CTA bus routes, and then to round $n_i$ to the nearest integer, i.e. 4.2 becomes 4, 4.8 becomes 5.

The bus allocation found by algorithm (4.1) uses the least number of buses possible in keeping with operator policies concerning vehicle capacity and with passenger definitions of acceptable paths. However, it is unrealistic in that it denies passengers with more than one acceptable path their choice of path. If an operator implemented an allocation found by this algorithm, he would likely find some routes overcrowded and others underutilized as variable flow passengers used different paths

than those to which the algorithm assigned them.

## 4.3 User-Optimized Passenger Assignment

While we can be quite confident in laying down the criteria for acceptable paths, it is difficult to predict accurately how variable flow passengers will distribute themselves among the acceptable paths. From the passenger point of view, it is quite simple: board the first bus that comes which belongs to an acceptable path and has room. When passengers follow this rule, what fraction of a given variable flow can be expected to board a route on an acceptable path?

The answer to this question depends on the distribution of bus inter-arrival times and whether there will always be room on the bus. Two distributions are studied in the literature: deterministic inter-arrival times and exponentially distributed arrival times [Lampkin & Saalmans, Chriqui & Robillard]. In Cairo the assumption of exponentially distributed arrival times seems more plausible. Under this assumption, and assuming there is room on every bus for passengers to board, a route's share of a particular market is given by:

$$P_i = \frac{q_i}{\sum_{j \in R} q_j} \qquad (4.1)$$

where $P_i$ = fraction of a particular variable flow that will use route i

$q_i$ = frequency on route i

$R$ = set of acceptable routes

Equation (4.1) is called the "frequency share rule" of passenger assignment, since each route's market share is proportional to its share of the total frequency offered by all competing routes.

If we want almost all passengers to be able to board the first acceptable bus that comes to their stop, then the bus allocation to each route, with the resulting frequency on each route, must be such that the capacity provided on each route is great enough to carry the loads that would be expected if all variable flows divided themselves among acceptable routes according to the frequency share rule. Finding such an allocation is an equilibration problem, since any bus allocation implies (by the frequency share rule) a passenger assignment, which in turn demands a bus allocation that provides adequate capacity. Many allocations will yield an equilibrium; we would naturally like to find the equilibrium that requires the least number of vehicles overall.

Han proposed the following algorithm for finding a near-optimal bus allocation that is consistent with the frequency share passenger assignment rule.

Algorithm 4.2

1. Assign captive flows to their unique paths.

2. Allocate buses to each route so that just enough capacity is provided to carry flows assigned in Step 1.

3. Assign variable flows according to the frequency share of each acceptable route.

4. Allocate buses to each route so that just enough capacity is provided to carry flows assigned in Steps 1 and 3.

5. If the bus allocation of Step 4 does not differ from the previous allocation, STOP; otherwise go to Step 3.

## 4.4 Application to Cairo

The two algorithms (4.1 and 4.2) presented in this chapter were applied to the Shoubra corridor in the North of Cairo.[1] The Shoubra corridor is bounded to the west by the Nile River and to the east by the Cairo/Alexandria Railway Line. While the corridor is served by buses, trains, and ferries, this study focuses on the bus service only, since buses provide the bulk of the public transport service in the corridor. This corridor is typical of the rest of Cairo with very high population densities and distinct activities scattered throughout. It is served by 34 bus lines on which more than 200 buses operate with a great deal of overlapping services.

Initially the set of bus routes was converted into a network of nodes and links and an inter-nodal demand matrix was determined from the 1978 O/D survey. This involved splitting the traffic analysis zone trip volumes into smaller units, so that trips could be more accurately assigned to the appropriate bus lines. Application of algorithms 4.1 and 4.2 resulted in allocations of buses to routes consistent with system optimized and user optimized assignments. As expected the system optimized required fleet size was smaller than the user-optimized fleet--in this case the difference was about 5% fewer buses for algorithm 4.1.

There were substantial differences between the actual allocation existing in 1978 and the allocations resulting from the algorithms for many lines. However, it was not possible to try to implement changes in

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[1] This application is described in detail in "Bus Allocation Procedure and its Application to Shoubra Corridor" by A. El-Badawy Taha.

allocation of buses based on this analysis because of important changes in Shoubra since 1978.

This application did show that both algorithms can be applied manually to a large network. Building on this experience, the next section suggests a comprehensive approach to bus allocation in the case of overlapping routes.

## 4.5 Suggested Procedure: A Compromise

Neither the system-optimized nor the user-optimized allocation is fully appropriate for Cairo. The system-optimized allocation is inappropriate because it assumes that people will use the routes CTA wants them to when, in fact, they won't; and the user-optimized allocation is inappropriate because the CTA is under no obligation to provide enough space to allow passengers to ride whatever route they want when they have other acceptable routes available that are less costly to provide service on. A compromise is appropriate: one in which passengers choose their routes freely, and then moves toward the system-optimized allocation by trying to influence passengers to use less costly routes. How far toward the system-optimized allocation the CTA can move depends on the effectiveness of the incentives and disincentives it applies to influence passenger route choice.

What kind of actions can the CTA take to influence passenger route choice? The simplest is the bus allocation itelf. Suppose the user-optimized allocation calls for 6 buses on Route 1, and the system-optimized allocation calls for 4 buses. If Route 1 is assigned 5 buses and passengers do not change their route choice from the user-optimized solution, Route 1 will become overcrowded. This crowding will influence

variable flow passengers to use a different route. If at the same time there is an overlapping, but less costly Route 2, whose system-optimized allocation is 7 buses and whose user-optimized allocation is 5 buses, and this route is assigned 6 buses, it will be undercrowded if passengers don't change their route choice, influencing passengers to use Route 2. By assigning 5 buses to Route 1 and 6 buses to Route 2, we are both influencing passengers to move toward system-optimized passenger assignment, and we are moving the bus allocation toward the system-optimized bus allocation. However, this kind of incentive must be used carefully, for in allowing overcrowding on a route one will not only be influencing variable flow riders to use a different route, which is good, but one may also be imposing an unfair hardship on captive flow riders who may be unable to board their route because it is overcrowded. In the morning peak this kind of incentive will usually work well, since most captive flow riders will be on board before the bus becomes overcrowded, and the crowding will primarily affect variable flow passengers. In the evening peak, however, the overcrowding affects variable flow and captive flow riders equally, so that the allocation in the evening peaks should probably lean more toward the user-optimized allocation while the morning peak allocation can lean more toward the system-optimized allocation.

There are other disincentives that try to influence variable flow passengers to use a less costly route without adversely affecting captive flow passengers in the evening peak. In Cairo, outbound radial routes are often filled at the downtown terminal. If the CTA wanted to keep variable flow passengers from using a route, they could make that route's

stop within the terminal as remote as possible, or even have it stop outside the terminal. Captive flow passengers would then be able to board, but variable flow passengers would prefer to remain in the center of the terminal where they would be more likely to catch buses on other acceptable routes. Then if the route did not have a layover in the terminal, but picked up its passengers and left immediately, the variable flow riders would be unable to board it.

The CTA might use other incentives and disincentives to influence people's route choice to move toward the system-optimized passenger assignment. Using proper judgement, it can apply these incentives to routes as appropriate, and move the bus allocation toward the system-optimized allocation. Then it must judge the effectiveness of its incentives by monitoring peak loads on the routes to which disincentives have been applied. If those routes are overcrowded to the point that captive flow riders are being hurt, then the allocation must move back toward the user-optimized allocation. If those routes are a little more crowded than normal, but operations are going smoothly, the allocation should remain unchanged. If those routes are just as crowded or less crowded than normal, then the CTA can continue moving toward the system-optimized allocation. In a stable solution it should be expected that the longer, more costly routes will be a little overcrowded, since this will help to influence variable flow riders to use a cheaper route; they should not be so overcrowded, however, that operations such as fare collection are unduly hindered, or so that captive flow riders are often unable to board.

## 4.6 Designing Overlapping Route Systems

The previous sections of this chapter have discussed how buses should be allocated in a set of overlapping routes. Now we raise the question, how can we find the best design of an overlapping route system?

The Cairo transit system is already full of overlapping routes, many of which exist to provide direct service between outer branches and the multiple downtown terminals. These routes should probably be kept unless a route's ridership is primarily made up of variable flow riders who would use less costly routes if that route were eliminated. The primary design issue is adding short routes in corridors where long routes already exist and trying to influence riders to switch from the longer routes to the shorter routes.

Adding a short route in a corridor is a potentially useful strategy when the loads on routes in the corridor are considerably higher over the inner segments of those routes than over their outer segments. By examining the load profiles of all the routes in a corridor, one can see whether there is potential for introducing a short route. If there is, one should choose (by judgement) its configuration or a few alternative configurations. One should then execute the system-optimizing and user-optimizing bus allocation procedures. Then one should decide which passenger route choice incentives can be applied, estimate their effectiveness, and move from the user-optimized allocation in the direction of the system-optimized allocation in accordance with the predicted effectiveness of

the route choice incentives. Then one can evaluate the new design with its vehicle requirements and passenger level of service, and compare it with the existing system and any other alternative designs, and choose the best one according to the CTA objectives and constraints.

# CHAPTER FIVE

## JOINT DESIGN OF EXPRESS AND LOCAL ROUTES

Express routes have three important advantages over local routes. Since they carry passengers from their origins to their destinations more quickly, they offer the operator a reduction in vehicular requirements, and consequently, operator cost. For the same reason, they offer passengers a better level of service. Finally, because of their special nature, operators will usually find it easier to charge a higher fare for express routes, and thus they can increase revenue.

In a system like Cairo's, virtually all express route passengers can be expected to be passengers diverted from local routes. Thus, the demand data needed can be obtained from counts on local routes. It is important to design jointly express routes and local routes that operate in the same corridor, since the introduction of an express route will affect demand for nearby local routes.

The design principles for express routes are:

1. Estimate the market that the express route will capture.
2. Adjust service levels on nearby local routes to reflect their loss in ridership.
3. Consider providing a zonal or overlapping system of routes for both the express service and the local service.

### 5.1 Express and Local Zonal Service with Exclusive Boarding and Alighting Zones

Chapter 3 showed how local zonal service could be designed with exclusive boarding and alighting zones. The same procedure presented in Section 3.1 can be used for designing express service. The issues

then are: what will be the service area (boarding area inbound, alighting area outbound) of the express route, and what share of the transit market will it divert from local routes? One can simply try a number of alternative express service areas, estimate the market share, and design the express and local service for the resulting demands. A more formal treatment of this subject is found in Furth's thesis. Since in Cairo it is unlikely that local zonal service with exclusive boarding and alighting zones will be implemented in a corridor along with express service, this strategy will receive no more attention.

## 5.2 Express and Overlapping Local Routes

The most likely implementation of express service in Cairo is in a corridor that already has overlapping local routes. The design procedure is then:

1. Suggest alternative express service areas. Analyze each separately.

2. Estimate the market that can be captured by an express route (or a few express routes) in that area. If it is below a certain threshold, an express route is uneconomical. If it is more than twice as great as the threshold, consider serving that area with two or more express routes. The final product of this step should be the layout(s) of the express route(s) with its (their) service area and estimated demand. For each proposed express route to be viable, its estimated demand must lie above the threshold.

3. Estimate the run times of the proposed routes, and compute the number of vehicles needed, which is

$$n_i = \frac{t_i d_i}{60C}$$

where $n_i$ is the number of buses needed on express route i (round to the nearest integer), $d_i$ is the heavy direction demand for route i (pax/hr), $t_i$ is the round trip time on route I (min), and C is the bus capacity.

4. The number of passengers diverted from each local route should be subtracted from the peak load of that local route to estimate that route's new peak load. The number of buses assigned to each local route should then be

$$n_i = \frac{t_i L_i}{60C}$$

where $L_i$ = revised peak load on route i

Repeat Step 4 for every local route in the corridor.

5. Sum the number of buses required on the express route(s) and on every local route in the corridor. Compute any other desired measures, such as predicted wait time, in-vehicle time, and revenue.

6. Repeat Steps 2-5 for each alternative express service area. Using the measures of operator and passenger cost computed in Step 5, select the best alternative in accordance with the CTA's objectives and constraints.

# CHAPTER SIX

## INTERCORRIDOR ROUTING IMPROVEMENTS

This chapter discusses ways to improve the efficiency of the Cairo transit system through routing changes that involve more than one corridor. Two types of intercorridor routes can be considered: crosstown routes, which join two or more corridors without traversing the downtown, and through routes, which connect two corridors through the downtown.

### 6.1 Crosstown Routes

In the absence of a crosstown route, passengers traveling between nearby corridors must use a radial route to get downtown and transfer to another radial route to get to their destination. For the passenger, this path is without question inferior to a direct trip on a crosstown route. For the operator, it can also be more efficient to serve crosstown trips on crosstown routes. If the passenger must use two radial routes, he will increase the peak load on both of these routes, requiring extra capacity on potentially long, expensive routes. If he uses a crosstown route instead, he will be on board for a shorter amount of time, lessening the chances that he will increase the peak load; and even if he does increase the peak load on the crosstown route, the extra capacity he requires will be used more efficiently than extra capacity on a radial route since crosstown routes don't have the severe directional load imbalances in peak periods that characterize radial routes, meaning that extra capacity on a crosstown route can be useful in both directions, not just in one direction as on a radial route.

To identify demand for new crosstown routes, one needs an origin-destination matrix of linked passenger trips which cannot be derived from route on-off counts or point counts alone. The on-board origin-destination survey performed in Cairo in 1978 is a useful source of data on linked passenger trips.

Given a zonal origin-destination matrix of passengers who currently must transfer between two or more routes, new routes can be planned to reach these markets. The procedure for planning a new route is heuristic, relying heavily on the planner's judgement. This seems to be more effective than one relying on extensive computation using a computer, since routing problems are very complex mathematically.

The suggested procedure given below includes both route layout and bus allocation.

A. Route Layout

Step 1. Select the zonal pairs whose transfer volumes exceed a certain threshold, say 75.

Step 2. On a map, color code these zone pairs according to the following guidelines:

a. The two zones of each zone pair should have a coding that is identical and different from that of every other zone pair.

b. The coding could also carry information on the magnitude of the transfer volume; e.g. use triangles for volumes between 75 and 150, circles for 151-250, and squares for > 250.

Step 3. Design the layouts of new bus routes in accordance with a knowledge of the street network by connecting the selected zone pairs in order to serve the greatest possible number of transfers. Note that both the origin and the destination zone of a zone pair must be included for its volume to count; hence the necessity of color coding zone pairs. The choice of layouts may be facilitated by the following suggestions:

a. To narrow the scope of the problem, work independently on smaller sectors of the city, e.g. look only at zone pairs contained within Shobra and Giza in designing direct services from Shobra to Giza. It will probably be useful to have a separate map for each sector.

b. If the coding carries information on the size of transfer volumes, give the zone pairs with higher volumes greater priority in laying out the new routes.

c. To get started, it will probably be helpful to select a zone pair with a large transfer volume and design the layout around this pair, adding other zone pairs to the route as seems reasonable within the constraints of using acceptable roads and avoiding circuitous routing.

d. Keep in mind that a zone is an area, so that a route passing through it may not serve the entire demand in that zone. Similarly, part of a zone's demand may be served by a route that does not traverse it, but traverses a neighboring zone.

The route layouts designed by these first three steps are not guaranteed to be optimal, and require creativity and intelligence on the part of the analyst. However, we believe that the coding scheme recommended above will provide the best visual aid to the analyst in designing routes that serve the zone pairs with the highest transfer volumes.

## B. Bus Allocation

Given a new route, the main problem is to estimate its ridership, and thereby determine the frequency and number of buses required to serve this demand. It is also important to estimate the impact on routes currently serving these demands.

Step 4. Determine the fare structure of the new route and also estimate its round trip time.

Step 5. Considering all the zone pairs served by a route (not just those coded on the map), and taking into account the influence area of the route in each zone, estimate the potential number of travelers between each zone pair who will use this service based on the matrix of transferring trips for the peak hour. If for any zone pair the fare for the new service is more than the fare for the trip on the previous path, estimate the number of travelers who are fare-sensitive and therefore will not not use the new service, and deduct them.

Step 6. Based on the volume computed in Step 5, estimate the volume at the peak load point, $V_1$. If it does not exceed a certain threshold, say 400 per hour, eliminate this route from consideration. Otherwise estimate the frequency of the new line as $\frac{V_1}{C}$, where

C = capacity of a bus (e.g. 100 pax/bus) and the threshold 400 is based on a maximum headway requirement (e.g. 15 minutes).

Step 7. We need to know from which lines the trips now served will be diverted. Some of this information can be found in the 1978 survey, but may not be readily available; at any rate, some must be estimated based on judgement. Using the rules of transit trip assignment described in Section 4.3, the trips diverted to the new route can be allocated among the existing lines. For each zone pair, compute the number of trips diverted from each relevant line.

Step 8. Compute the decrease in required capacity on each affected existing line (i.e. the difference between the former and new peak load point volumes). Compute the reduction in number of buses needed on each line due to this reduction in required capacity.

Step 9. The reduction in number of buses needed on other lines should exceed the number of buses needed on the new route because the demands are served more directly. Problems may occur, however, due to the integral nature of buses (e.g. it may not be possible to take 1/4 of a bus from each of 24 lines to get 6 buses for a new line). The final reallocation of buses therefore relies on the planner's judgement and the numbers computed above. As well as the existence of new or surplus buses.

The reallocation procedure may point to a reduction in the need for buses on certain lines, while the planner may want to leave the buses there. Nevertheless, the reduction in number of buses needed should be evaluated as a benefit, since it will reduce crowding and/or provide some slack that will later be taken up by the needs of other lines. Care must be taken that the headways on existing lines do not rise above the policy maximum.

## C. Evaluation

The third part of the procedure is the evaluation of the proposed routes and selection among them. The criteria for selection should be:

1) A selected route should have positive benefits

2) A selected route should have greater benefits than that of any mutually exclusive alternative.

The benefit measures of a proposed route are the number of transfers saved and the number of buses saved. These two factors should be weighed approriately and a composite benefit measure computed for each line.

If all routes are independent, every route with positive benefits should be selected. If a number of routes are mutually exclusive, the best alternatives should be selected. A problem occurs when routes are neither independent, nor mutually exclusive, as illustrated in Figure 6.1. In order to avoid double counting benefits, such a set of interdependent lines must be analyzed and evaluated together, affecting Steps 5-8.

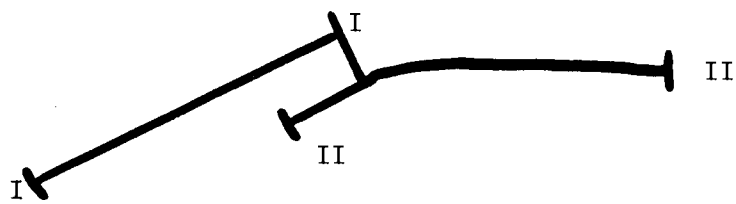
Step 10. Among independent sets of mutually exclusive alternatives, select the alternative with the greatest benefits provided the benefit is positive; select no member of a set if the benefit is not positive.

## 6.2 Through Routes

Through routes are generally discouraged by the CTA because its fare policy forbids collection of fares that are commensurate with the long distance covered by a through route. By making passengers transfer downtown between two radial routes, two fares can be collected from passengers making long trips from one side of the city to another. However, the Greater Cairo Bus Company (GCBC) has recently created a number of through routes for which it is allowed to charge higher fares (10 piastres), and there is no reason more through routes could not be made part of the GCBC system.

FIGURE 6.1

TWO INTERDEPENDENT ROUTES THAT ARE
NEITHER INDEPENDENT NOR MUTUALLY EXCLUSIVE



Because through routes, where implemented, will usually have higher fares, it would be unwise to assume that all passengers who now transfer but could use a new through route to make their trip direct will switch to the new route. Furthermore, the large number of possible paths a through trip may now take (transferring at any one of a number of squares, using different routes to and from each square) makes it preferable to use data on transfer trips such as the 1978 O-D survey and to use the procedure of Section 6.1 to plan these new routes, considering the demand impact of the higher fare in Step 5.

Ignoring for a moment the fare problem, there is a way that the efficiency of CTA operations could potentially be enhanced through the creation of through routes. At present there are many radial routes originating south and west of downtown that pass through Tahrir Square and terminate at Ramses Square, while other radial routes originating north and east of downtown pass through Ramses Square and terminate at Tahrir Square. This configuration provides twice as much capacity as would normally be expected over the Tahrir-Ramses segment. By combining two routes of similar frequency, some operating cost would be saved since the Tahrir-Ramses segment would be covered only twice per round trip compared with the current four times (twice for each radial route). No extra passenger transfers would be required in such a scheme. The only problem with this scheme (besides the fare problem) is that passenger capacity on the Tahrir-Ramses segment would be reduced.

# CHAPTER SEVEN

## THE DESIGN OF NEW DIRECT BUS SERVICES IN GREATER CAIRO

As discussed in the previous chapter, the introduction of new inter-corridor bus services, referred to as "direct service," is one of the strategies available to improve transit system performance in Cairo. In this chapter the procedure used by the research team to identify new direct service opportunities is presented (it is a variant of the procedure described in Chapter 6) and the results of the analysis described.[1]

### 7.1 Procedure Description

The following procedure is adapted from the principles set forth in Chapter 6, the aim being not to eliminate any existing services, but rather to reduce the number of transfers between some origin-destination (O/D) pairs in Cairo. The basic data used in this procedure is the matrix of the number of transfer trips at the interzonal level. In this case this trip matrix was derived from the 1978 CTA on board survey modified to account for demand growth since 1978. The procedure is as follows:

Step 1. Using the peak hour matrix (in this case the 8-9 a.m. period was analyzed), list in descending order the top 20 subzones according to the total number of passengers who make trips involving a transfer.

Step 2. Select the highest subzone on this list which has not yet been considered; this will be referred to as Subzone A. Identify all subzones having more than 75 passengers per hour[2] going to or from Subzone A and list these subzones in tabular form.

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[1] The work summarized here is described in detail in "Procedure to Identify New Direct Bus Services in Greater Cairo" by M. El Hawary, F. Model-Bary, T. Esmail, and A. Montasr.

[2] This volume was selected based on experience and an examination of the O/D matrix for transfer trips.

Step 3. Mark Subzone A and the associated subzones on a map with color-coding. From an examination of the map, identify sets of these subzones which could form new direct lines serving Subzone A.

Step 4. Identify all the other subzones not listed in Step 2 but served by the new line. If the line passes near a subzone, a percentage of that subzone's volume will be assumed to select the new line.

Step 5. Estimate the potential ridership of each new line by summing all the transfer trips between the subzones identified in Steps 2 and 4.

Step 6. To justify establishing the new direct line and to ensure adequate service frequencies the following assumptions can be made:

- The maximum acceptable mean headway in minutes, $H_{max}$ = 10 minutes
- The nominal bus capacity in passengers, k = 100 passengers

If the maximum demand $V_\ell$ on the suggested line is greater than or equal to $(\frac{60}{H_{max}} .k)$, then the line is feasible. If this condition is satisfied, i.e. $V_\ell \geq 600$ passengers, proceed to Step 7, otherwise return to Step 4 to investigate the addition of more subzones.

Step 7. Estimate the one way running time T for the new line using data gathered for the existing bus network.

Step 8. Calculate the number of buses required to serve this line

$$n = \frac{V_\ell}{k} \times \frac{2T}{60}$$

Insert the new line into separate ranking of all new lines based on the maximum demand $V_\ell$. Return to Step 4 or 2 as appropriate until all candidate lines and the whole subzone list have been considered.

## 7.2 Results in Cairo

The procedure described in section 7.1 was applied in Cairo making use of the 1978 O/D survey results. It should be noted that this procedure was designed for manual solution and no computers were used in the Cairo application. A total of twenty-seven new direct lines were developed

in step 3 of the procedure, but these were reduced to thirteen through the constraints in step 6. Each of these proposed new lines was carefully reviewed by CTA planners who made valuable suggestions to improve terminal selection and paths between terminals. In some cases a new line was extended to end at a more suitable terminal.

After these reviews CTA implemented seven of the thirteen proposed new lines. All of these lines are still in operation showing high ridership and productivity. The remaining new proposed lines will be implemented when additional buses become available.

This experience supports the value of adding carefully selected new inter-corridor bus services in terms of improving vehicle utilization as well as improving the service provided to the public. The suggested procedure proved to be effective in identifying productive new services, although careful review and modification by experienced local planners is essential.

# CHAPTER EIGHT

## CONCLUSIONS

As stated at the outset, this research focused on just one aspect of the public transport problem in Cairo; the development of improved methods for bus service planning. At the present time it is premature to judge the success of these efforts, but certain conclusions can be reached:

1. Manual procedures have been developed and shown to be feasible to identify changes which might improve productivity, and in many cases service quality, at the level of the route, corridor and inter-corridor markets.

2. These methods are in general feasible with the types of information resulting from passenger, revenue, and ticket counts and are not dependent on expensive and time-consuming on-board surveys

3. Results of these procedures should be viewed as the input to a review process by the planning staff with the experience, judgement, and local knowledge to identify weaknesses and suggest improvements.

It is clear that the types of service improvements which can be identified by these procedures are not easily found by other planning methods, and that they do have potential for positively affecting public transport in heavily used, under-equipped public transport systems, such as Cairo's.

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## APPENDIX

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