CET

COMPANHIA DE ENGENHARIA DE TRÁFEGO

boletim técnico

COMONOR

9

COMBOIO de ÔNIBUS ORDENADOS

COORDINATED BUS CONVOY

special issue in english

Comonor

Comboio de Ônibus Ordenados

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Comonor

Ordinated Bus Convoy

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Companhia de Engenharia de Tráfego CET

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This series of Technical Bulletins is intended to divulge important traffic and transportation studies and projects developed by CET — Traffic Engineering Company's technical staff,
as well as those from other entities whenever considered relevant.

We believe this to be important, not only because it is an efficient way to report important study findings, but principally because it provides a specialized technical reference source for those working with or needing information in this field.

eng. Roberto S. Scaringella

This technical bulletin describes the implementation of a "Coordinated Bus Convoy System" in one of the heaviest traffic corridors in the city of São Paulo, Brazil.

The present special issue in English was prepared due to the interest on this subject shown by foreign traffic and transportation technicians.

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summary

With the intent of increasing capacity of boarding passengers at bus stops along 9 de Julho Ave. (São Paulo, Brazil), CET has developed the COMONOR Project (Coordinated Bus Convoy). The bus stops were found to represent the points of critical capacity along the exclusive bus lanes of such avenue, and, as a result of this project, the boarding passenger capacity has been increased several-fold with a minimum of investment.

Since implementation, the exclusive bus lanes along 9 de Julho have not attained full operational efficiency due to the high bus volumes and the passenger boarding process at the bus stops where each had to stop, open the doors, wait the passengers to board and unboard, close the doors and depart. After this slow process, another bus would arrive at the same point and repeat the same step by step operation. The COMONOR Project was able to increase the bus boarding capacity by more than 100% by allowing the buses to operate like a subway train, with several buses stopping simultaneously, boarding their passengers, and departing in a queue or "convoy" at the same time.

The original concept adopted was, first, to divide the bus lines into fixed groups (A, B, C etc.) at a bus terminal located at the beginning of the corridor so that each group could be coordinated and move as a "system" or coordinated convoy. The bus stop locations were also divided into sub-areas for passenger boarding in the same order. On 9 de Julho Ave., the site of the pilot project, the scheme actually adopted was to use a 3-group division (A, B and C). Buses were organized into pairs, in sequence, forming a convoy of up to 6 buses (AA, BB, CC). Using this scheme, the average operating speed during the afternoon peak period was increased from 10 to 19 km/hour (a 90% improvement) along a 4 km. section of the avenue, thus saving 11 minutes per trip. Some of the characteristics of this 4 km. section include 6 bus stops, 5 traffic signals, and 300 buses per hour carrying an average of 12,000 passengers.

Our evaluation, after implementing this scheme, suggests that it may be possible to reach a capacity of 27,000 passengers/hour/direction (450 buses/hour/direction), but also having a minimum limit of applicability of about 140 buses/hour/direction.

2
exclusive bus lane capacity

In an effort to improve public transportation and support the fuel rationing efforts, DSV — Department of Street System Operations, proposed a program for implementing exclusive bus lanes in order to allow the buses to be relatively free flowing without congestions, interference from other vehicles, to increase bus operating speeds, and thus improve service for bus patrons. However, many of the principal arterial streets, or corridors, are totally saturated by large volumes of buses which often use the second lane for passing maneuvers etc. This presents the following questions: at what point is it advantageous to use exclusive bus lanes when the volume is very large? and, how many buses can reasonably be accomodated in only one lane?

The answers are quite simple.

As long as buses are required to use only the exclusive lanes, and cars are prohibited from using them, there is always an advantage. When the exclusive lane is flowing better than the others, the bus will use it and when it is loaded they can also use the other lanes.

In a bus lane having no traffic signals, one bus may pass a given point during each 3.5 seconds, which means a 1,030 bus/h. capacity. If there are traffic signals, the capacity is approximately equal to 1,030 multiplied by the percentage of green time of the total cycle for the corridor in question. The traffic signals on the majority of the traffic corridors have at least 60% of green time, guaranteeing a capacity of 618 buses/h. which is higher than the normal demand for any corridor. Therefore, if traffic signals were the only point to be considered, one bus lane would be sufficient for any traffic corridor in São Paulo.

Below is a summary of the bus volumes for each of the principal corridors in São Paulo. As can be seen, all volumes are less than the 618 buses/hour/direction capacity limit discussed previously.

CORRIDOR	BUSES
Celso Garcia—Rangel Pestana Ave.	500
Radial Leste Ave.	350
São João Ave.	300
Nove de Julho Ave.	300
Estado Ave.	200
Rio Branco Ave.	250
Santo Amaro Ave.	270

We therefore found the real critical points of the corridors to be at the intermediate bus stops, where each bus takes about 12 seconds to arrive and depart, plus 2 seconds per boarding passenger, and another 1.2 seconds for each passenger getting off the bus. Example: if along the route the average number of boarding passengers is 4, there will be a 20 second (12 sec. + 8 sec.) time loss per bus. Therefore, the maximum capacity for each point will be 180 buses/hour (3,600 seconds per hour + 20). If the bus stop is very close to a traffic signal (before or after) the problem becomes worse. During the time that the signal is red, the bus will remain stopped, even after the passengers have boarded, thus reducing its efficiency. Therefore, without consideration of other factors, the capacity of a bus stop may be expressed as follows:

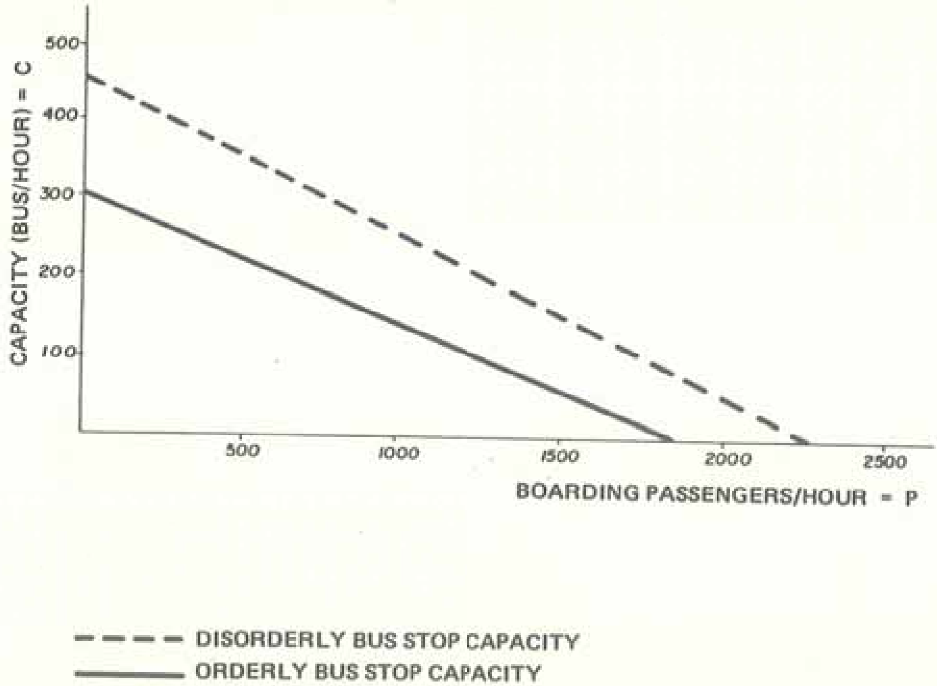
$$C = \frac{3.600 - 2p}{12} \text{ where}$$

C = capacity in buses/hour
p = boarding passengers/hour

As can be seen, the greater the number of boarding passengers at a given point, the less will be the capacity. In São Paulo, the number of buses is generally constant throughout the day, but the number of passengers increase significantly during the peak hours. When the capacity (in buses/hour) decreases in relation to demand, bus queues begin to form and waiting passengers begin to occupy space away from their established boarding points. Because of this each vehicle must stop more than once and passengers have to run, many times missing the bus, in a disorderly boarding area that often creates confusion. It is not unusual for a passenger to be as far as 100 metres from the bus stop in a queue with other passengers. Although it seems incredible, this increases bus boarding capacity by approximately 50%. It was found through empiric observations that the capacity of a disorderly bus stop can be expressed as follows:

$$C = \frac{3.600 - 1{,}6p}{8}$$

We therefore have the following limits:



As can be seen, all corridors, except Celso Garcia Ave., can support the normal buses demand if the number of boarding passengers per bus stop is low.

Normally, the problem of high boarding passenger volumes occur during the afternoon peak or the work/home trip (CBD/suburbs).

During the morning peak, the boarding passengers are dispersed along initial sections of the bus routes in the suburbs, without high concentrations of demand. Near the corridors with higher densities, the suburb/CBD boarding passengers generally are offered few alternate routes, which facilitates boarding, decreases waiting time, and decreases the number of passengers at each bus stop. Getting off the bus does not represent a problem because when the buses stop (even in a convoy) all passengers get off at a very fast rate.

3
traditional solutions to improve bus stop efficiency

The major problem to be resolved is boarding passengers destined for the suburbs during the afternoon peak. Some solutions adopted were:

Route variation

Vary routes to avoid having them concentrated in the same corridor. From a traffic point of view this is the best solution because, by dividing the bus fleet in 2 corridors, we have the potential of 2 exclusive bus lanes which can double the capacity. The only disadvantage is that frequently there is no alternate corridor to be used or, if there is an alternate corridor, it can't be used because of incompatibility of the transport improvement with existing land use.

Increase the number of bus stops

With more bus stops, the number of passengers at each stop will be smaller, thus increasing lane capacity. The basic disadvantage is the decrease in vehicle operating speed, plus the difficulty of finding adequate locations for the desired additional bus stops.

Alternate bus stops

This plan fundamentally consists of dividing the bus fleet into 2 groups, according to the route, with an exclusive bus stop for each group. The results will be that each bus stop will be accomodating half the number of buses and passengers that it previously did, thus increasing capacity. For the vehicles, this system is as efficient as alternating the bus routes. The disadvantages would be the mixing of buses at each bus stop and passing which presents traffic safety problems. It also requires that the passengers know exactly where their bus stop is located. This concept is widely used in Rio de Janeiro, Brazil.

Bus boarding islands

This recommendation is similar to alternate bus stops but has no vehicle mix problems. One group of bus lines travels in the curb lane and stops by the sidewalk, and the second group travels in the third lane and stops at the boarding island which occupies the second lane. The disadvantage of this recommendation relates to safety problems for vehicles alongside the islands and the utilization of 3 lanes for public transportation which decreases capacity for automobiles. This solution was adopted at Celso Garcia Ave., in São Paulo, Brazil.

Line-hall transport recommendations

These recommendations create alternate routes for excess buses; subway integration to decrease some corridor lines; direct buses which do not stop along critical corridor sections or which use alternative routes; and the establishment of exclusive trunk lines for transportation to an intermediate transfer point, facilitating boarding and making possible more homogeneous lines with less buses.

4

the convoy solution and its efficiency at bus stops

When the basic capacity problem is at the bus stop the solution is to increase its capacity. If buses operate as a convoy similar to a subway train, and passengers board simultaneously, the bus stop capacity will increase substantially. A convoy of n buses requires a fixed time of 8 seconds to arrive and depart, plus a variable time of 4 seconds/bus for the convoy to move through the area, plus another 2 seconds per passenger who boards the bus in highest demand. Therefore:

$$TC(n) = 8 + 4n + 2.MAX(P_i)$$

TC (n) = total time the convoy spends at the bus stop (seconds)
n = number of buses in the convoy
Pi = number of passengers boarding bus i of the convoy
MAX (Pi) = maximum number of passengers boarding a convoy bus

CONVOY PERFORMANCE SCHEDULE

BUS	number of boarding passengers	Boarding time (seconds)		
		only one orderly bus stop	only one bus stop	convoy boarding
A	4	20	14,4	—
B	2	16	11,2	—
C	6	24	17,6	—
D	10	32	24,0	—
E	8	28	20,8	—
F	5	22	16,0	—
TOTAL		142	104,0	52
Average time/bus (seconds)		23,6	17,3	8,66
Capacity (bus/hour)		152	208	418

As can be seen above, a convoy can reduce boarding time per bus by half, doubling the bus stop capacity (in buses/hour) by using only an exclusive bus lane, thus eliminating the need for construction of special bays, alternate bus stops, additional bus stops, or removing the buses from the lane. This capacity increase can be explained as follows:

Simultaneous bus arrival and departure

Each bus takes 12 seconds to arrive and depart, of which 4 seconds correspond to the interval between 2 buses and can't be decreased, and 8 seconds correspond to lost time for bus deceleration entering the bus stop area, opening and closing of doors, and acceleration while leaving. In a bus convoy, the stops, departures and opening and closing of doors, are simultaneous and the 8 seconds are divided by the number of buses. Therefore, a 6-bus convoy spends about 4 + 8/6 = 5.3 seconds instead of 12 to stop and leave the bus stop area. This represents a reduction of 55% in the time loss as compared to the orderly boarding of only one bus, or 34% as compared to disorderly boarding.

Simultaneous passenger boarding

Instead of boarding one bus at a time, passengers board n buses at the same time (n = 6). Therefore, the time spent is not divided by the number of vehicles, since the number of boarding passengers is not the same on all buses, and some buses have to wait the departure of a higher demand bus. Tests showed that boarding time per passenger can be approximately expressed as follows:

$$t = \frac{6}{2 + n} \text{ where}$$

t = time spent per boarding passenger (seconds)
n = average number of buses in the convoy

For example, in one convoy of 6 buses, t = 0.75 with a reduction of 62% in relation to the orderly boarding of a bus each time, and 50% in relation to a disorderly boarding.

Consequently, these two cases of bus stop capacity may be expressed in buses/hour by:

$$C\ (n) = \frac{3.600 - 6p/(2 + n)}{\frac{(8 + 4n)}{n}} \text{ where}$$

C(n) = capacity in buses/hour
p = number of boarding passengers/hour, and
n = average number of buses in the convoy

Figure 1 shows the bus stop capacity in buses/hour, in relation to boarding passengers demand/hour at the bus stop, and to the average number of buses per convoy.

As can be seen, the bus stop capacity increases considerably with a convoy operation, up to the theoretical limit of 900 buses/hour for large convoys. Therefore, all bus corridors in São Paulo could solve the "lack of convenience" problem at bus stops through the proper use of adequately sized convoys.

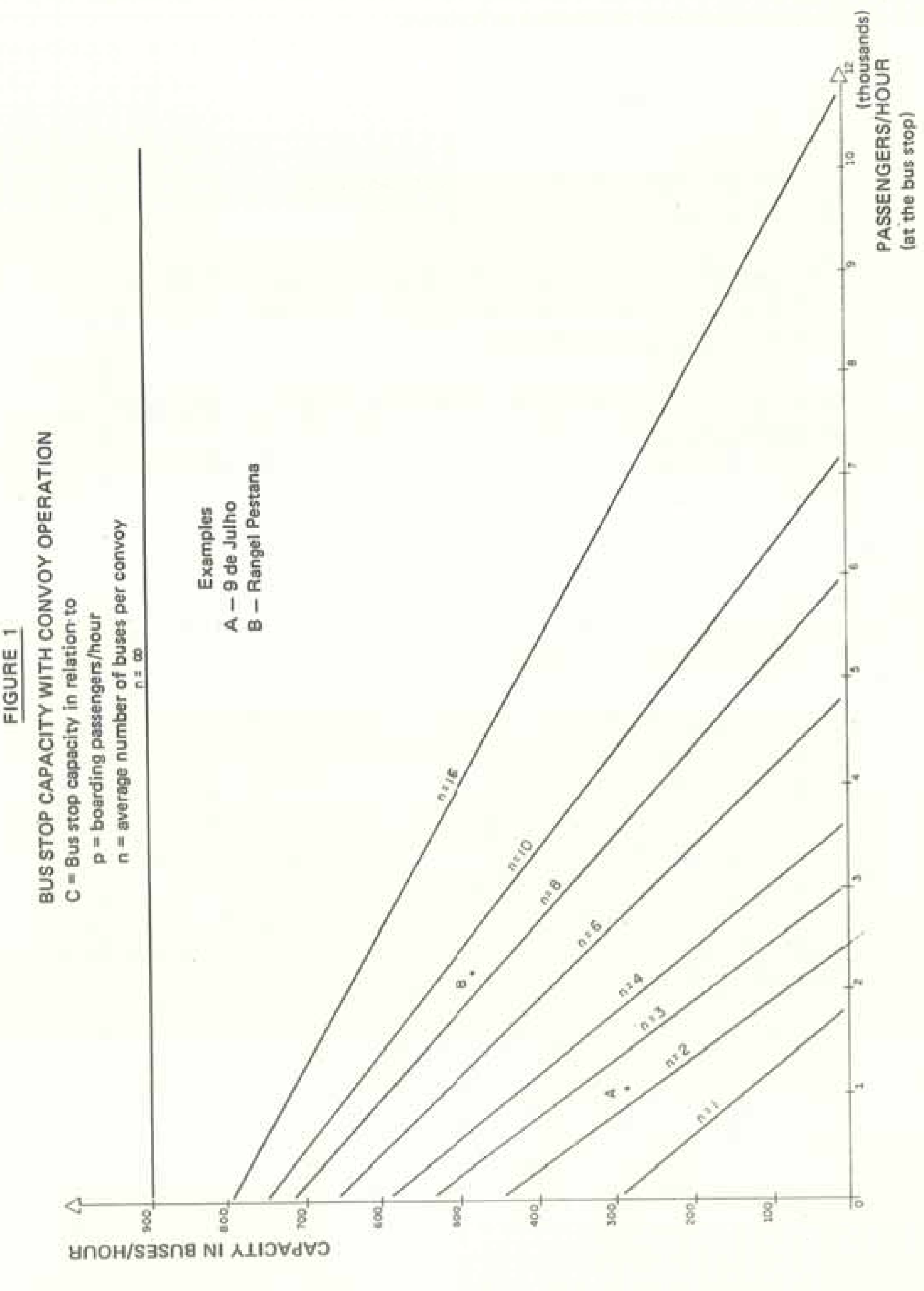


FIGURE 1

BUS STOP CAPACITY WITH CONVOY OPERATION

C = Bus stop capacity in relation to
p = boarding passengers/hour
n = average number of buses per convoy

5
bus-passenger coordination methods

Having proven, theoretically, that a convoy system would be an efficient method to increase capacity, the next problem consisted of developing a scheme which could provide order for passengers of the buses so that when the convoys arrived, each passenger was positioned near the bus he wanted to board (on the Metro this problem does not exist because all the cars of the train have the same destination).

The first idea to organize the passenger, through the use of visual communications which would advise passengers of which bus was arriving next at the bus stop (this system was used in Rochester, USA) was quickly abandoned for three reasons:

1) high cost and the long time necessary to install the computerized control equipment, detectors, communications etc.

2) Difficulty in providing information on buses to arrive at six different bus stops where, each 45 seconds a convoy could arrive.

3) necessity of passengers to walk as far as 60 metres to catch their bus, in a time of 60 seconds, which would make the high concentration of persons in the bus stop area even worse than the old system.

The second idea was to divide the bus line into groups (ABC etc.) in an orderly sequence, and to release the bus convoys in the same sequence (A, B, C, ...) which could coincide with the sequences established for the sub-area at the bus stops.

This idea resulted in several advantages: the cost of implementation would be practically nothing, the passengers waiting for their bus would always use the same sub-area, and the bus drivers would always stop at the same place at the bus stop.

With this scheme, there was only one problem: how to coordinate the buses at the beginning of the corridor?

The various techniques and analysis that were initially used may be found in the appendix.

A summary of the method which was finally adopted is as follows:

The bus stops were determined for each line, and were organized at an Initial Coordination Station at the beginning of the corridor.

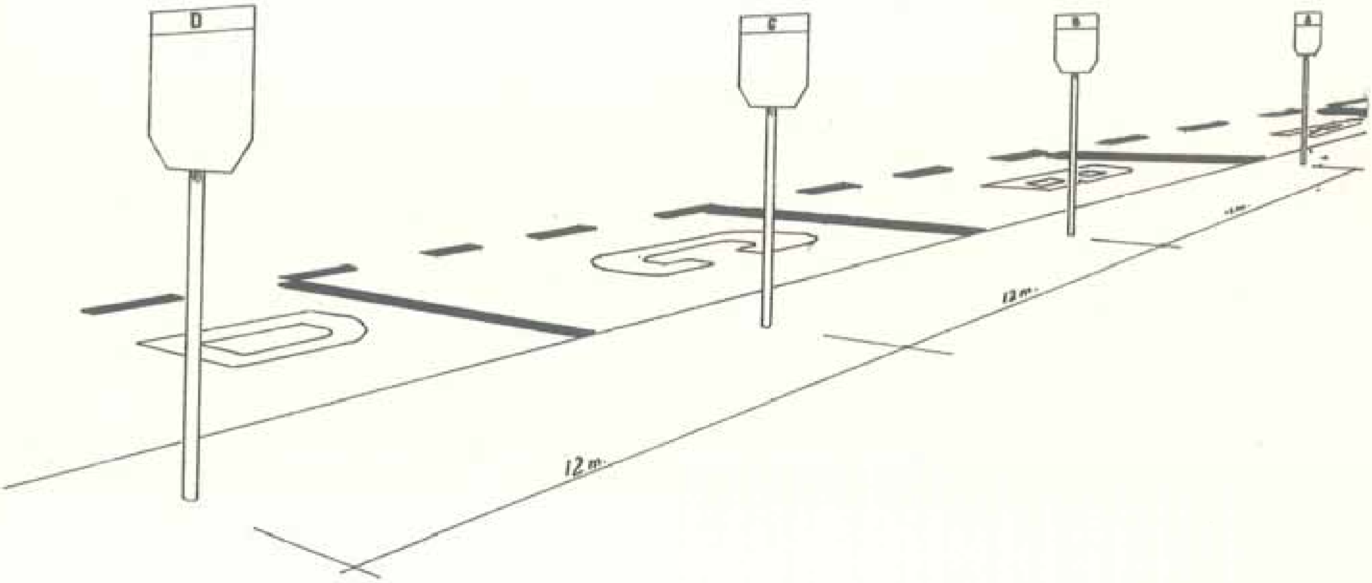
The bus lines were divided into n groups in the same order as the sub-areas at the bus stops, with each group having about the same frequency of buses and number of boarding passengers.
At each n sub-area bus stop, signs were installed showing the line serving each sub-area for the bus stops so that passengers would know were to board their bus. For those passengers who could choose more than one bus line, as many buses as possible were placed in one group which served the same area.

The project, thus seeming more feasible, justified choosing a corridor and preparing the design for the project. If after preparing the design concept it would yet appear feasible the experiment would be implemented.

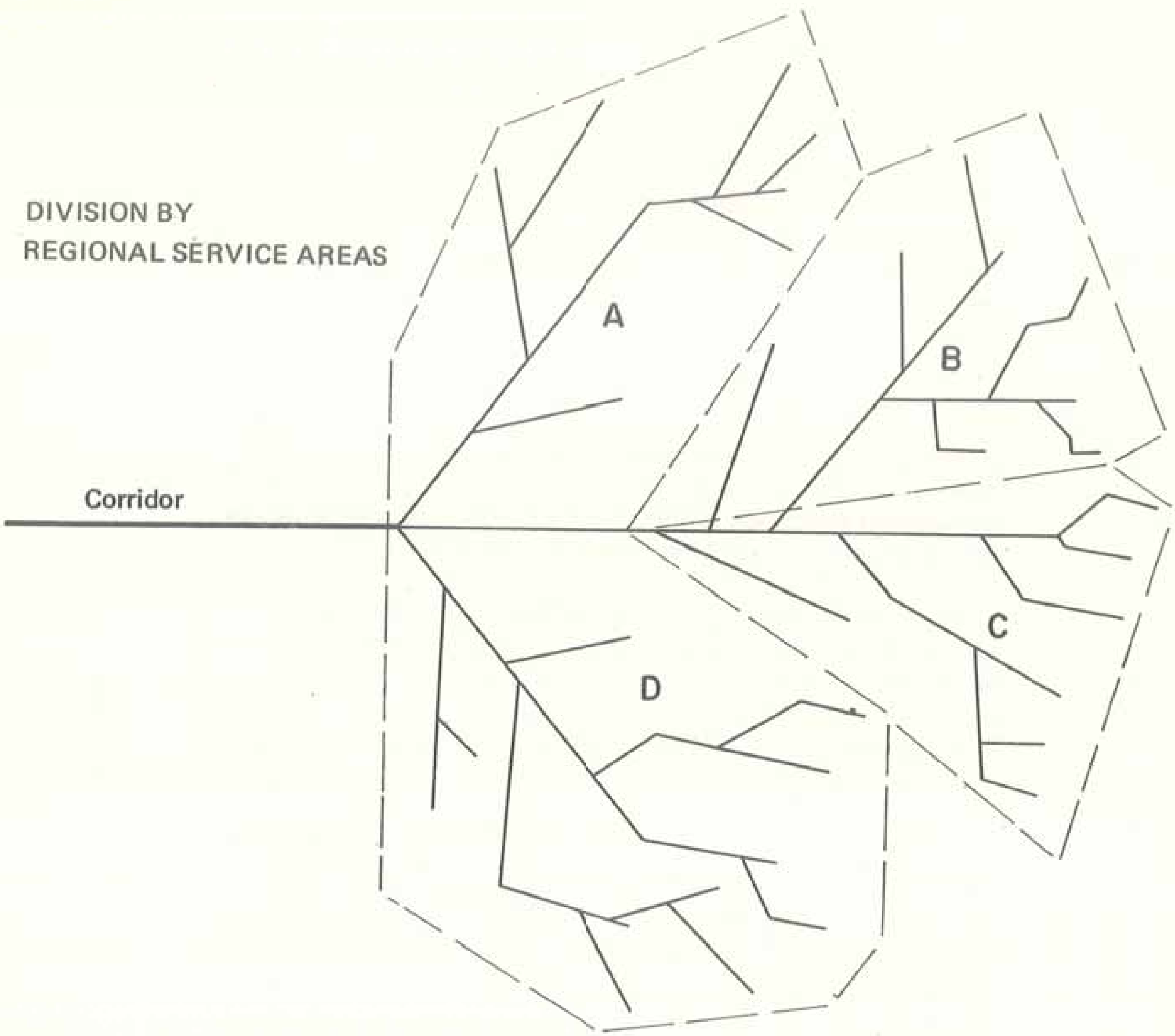
6
9 de julho corridor feasibility study

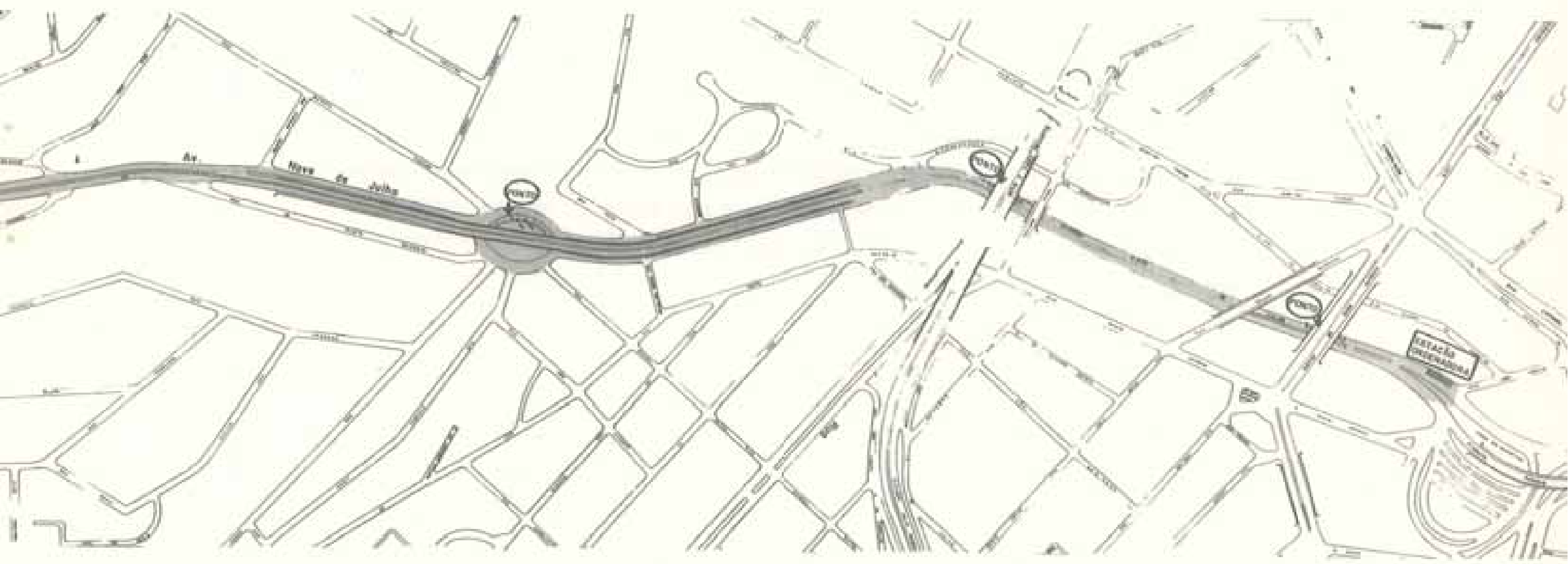
9 de Julho Ave. was chosen for the pilot project, principally because it was the corridor with the worst congestion problems at bus stops in the afternoon peak hour, with 300 high demand buses and a bus stop capacity (before the pilot project) of only 240 buses/hour.
9 de Julho Ave. is about 4 km. in length between Bandeiras Sq. and Estados Unidos St. After implementation of the exclusive bus lane, the travel time for this section (during all hours except the afternoon peak) was approximately 10 minutes with an average speed of 24 km/ /hour which can be considered excellent for a traffic lane carrying 300 buses/hour through five traffic signals.
But the heaviest congestion occurred during the afternoon peak hour, principally in the CBD/suburb direction. The peak hour volume of boarding passengers/hour at the critical bus stops between José Maria Lisboa St. and Estados Unidos St. increases to about 1,000 passengers/ /bus stop/hour. The period of heavy congestion occurs between 4 pm and 8 pm. Lines of buses near the bus stops are often as long as 500 metres with a travel time increase of up to 24 minutes, which represents an additional delay of 14 minutes in relation to the peak hour. This causes a decrease in travel speed from 24 to 10 km/hour and, principally, a large amount of disorderly boarding of passengers which creates problems for both passengers and drivers.

EXAMPLE OF BUS STOP SCHEME WITH 4 SUB-AREAS



DIVISION BY
REGIONAL SERVICE AREAS





In these cases, the drivers have to travel about 80 m. watching for potential passengers with a considerable increase in stops and opening of doors, or the passengers must check all buses to determine which is his, then run to board it. At other times, after several stops at the same bus stop, the bus driver often departs leaving behind some passengers, or he may choose not to stop at all in order to avoid the queue.

To evaluate the feasibility of the project, a survey of the most critical bus stop (José Maria Lisboa St.) was made to determine the number of boarding passengers, the number waiting, and those already on the buses during each time interval and at each area near the bus stop. Calculations were made related to bus frequency (by line) as well as the trável time during different periods of the day.

These data indicated that a convoy of 3 or more buses would be sufficient to increase boarding capacity to the point where congestion would be eliminated. In effect, 200 buses/hour would form 100 convoys, each having a 20-second stop and departure time, totalling 2,000 seconds. With 1,000 passengers/hour there would be an average of 3.3 passengers/bus.

Considering that there is no uniform distribution because each bus transports a different number of passengers, simulations showed an average of 5.8 passengers within an 11.6 sec. boarding time per convoy, or 1,160 seconds for 100 convoys. Therefore, the bus stop would be occupied for 3,160 sec. of the 3,600 seconds available during the peak hour, at a satisfactory saturation level of 88%.
Considering that a medium convoy is always inferior to a maximum convoy, due to irregular bus arrivals, the maximum convoy should have 4 or more vehicles.

The maximum size of a convoy was established at 7 vehicles due to lack of more space at bus stops. A 7-bus convoy occupies 80.5 metres which, in most cases, is the practicable usable limit of some street blocks where the bus stops are located. Furthermore, since the heaviest volume bus stop is located between two traffic signals with spacing of about 220 m., it would not be convenient to have a convoy larger than 1/3 of this distance (i.e, 73 m.). Therefore, the different alternatives which were simulated consisted of ranges from 3 to 7-bus convoys.

Various alternative configurations were tested using computer simulation to evaluate previous calculations related to the average size of the convoy, average waiting time and operation complexity. After such analysis, it was found that the most efficient division of a convoy was in 3 groups (A, B and C), with 2 buses in each group, forming a maximum convoy of 6 buses (A, A, B, B, C, C). It was also determined that the most effective location to form the convoy was immediately after João Adolfo St. where the 9 de Julho Ave. has sufficient width and space. At this location it was possible to provide 3 parallel lanes of 3 m. each which could be used as the coordination station, and where the buses from groups A, B and C could be classified and lined up at a traffic signal. This procedure resulted in an average convoy of 4.7 buses with an average waiting time of only 15 seconds/bus.

The simulations predicted a 360 bus/hour capacity on the highest volume bus stop with a 20% capacity reserve in relation to a demand of 300 buses. With all problems solved at the theorical level, the project was approved in August'77, designed in September and implemented on October 1st.

7
project detailing

Bus stop layout

The bus stops were divided into 3 sub-areas (A, B, D) with enough space for 2 buses at each area, or 23 metres.

To delineate the passenger boarding areas to each region, 0.80 x 1.60 m. signs were placed perpendicular to the street to provide information about the bus lines and numbers of the bus groups stopping at the bus stop. The sidewalks were painted with a 50 cm. wide colored line near the curb. Colors chosen were:

Group A – Green
Group B – Yellow
Group C – Blue

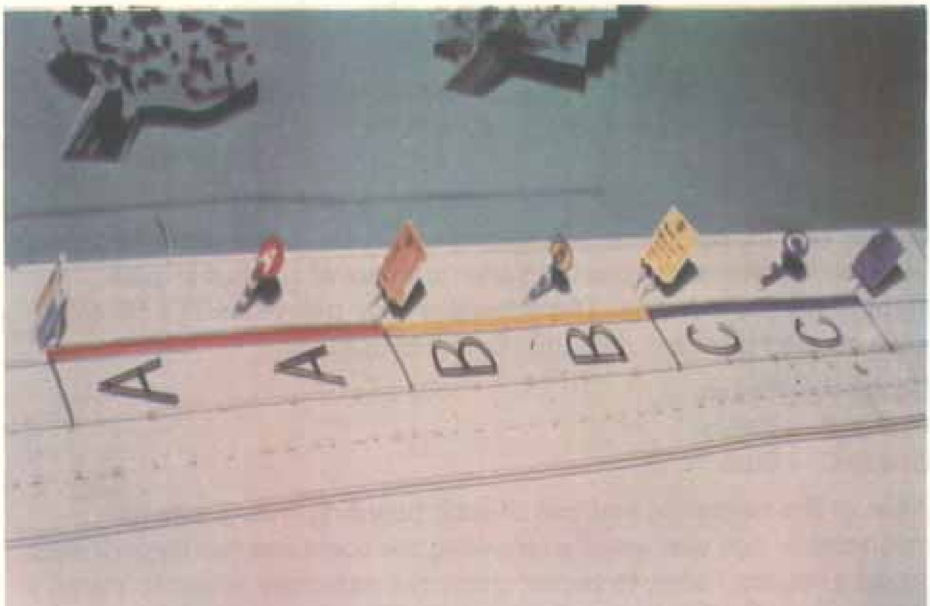
Also, at the beginning and end of each boarding area, a general information sign was installed showing the color and numbers of each group of buses. Later, to better orient the passenger where to stand, a standard CMTC (Municipal Transit Company) bus stop post was placed in each sub-area at a point equidistant between the boarding doors of 2 buses within the same group. On each of the bus stop posts were installed two 50 cm. dia. signs showing the letter and color of the respective group. To help orient the bus drivers as to their stopping area, stop lines were painted on the pavement at the beginning of each sub-area with corresponding letters repeated twice for areas A and B, and 3 times for C.

Bus stop location

Whenever possible, existing bus stop locations were maintained and were increased in length to 70 m. Special care was given to bus stops near traffic signals, because, when they are located before the bus stop, they can divide the convoy during a change in phase. When located after, a line of buses accumulated at a red signal may form a queue so long that it may block the bus stop area for an approaching convoy, thus reducing its performance. At regular bus stops (with no convoy) there are quite simple criteria which may be used to analyze the mutual influence of bus stop/traffic signal. This influence becomes more complicated when convoys are concerned, and simulations were made using different bus stop locations and traffic signal offsets to choose the best sites.

GENERAL CHARACTERISTICS

Of the 8 bus stops existing at the time, 2 were eliminated due to low demand, thus concentrating all the demand at 6 points along the 4 km. corridor. The bus stop layout is identical for all 6 points.



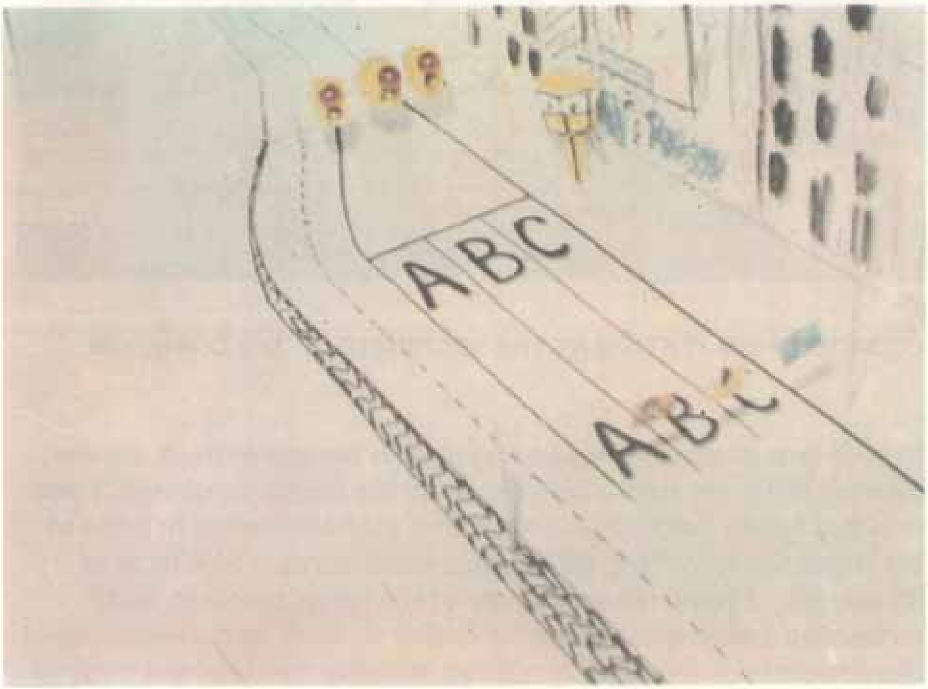
SCHEME

CORRIDOR

GENERAL LAYOUT OF THE CORRIDOR

Coordination station

The location chosen for the coordination station is immediately after the exit of João Adolfo St. where 9 de Julho Ave. has a maximum



LAYOUT

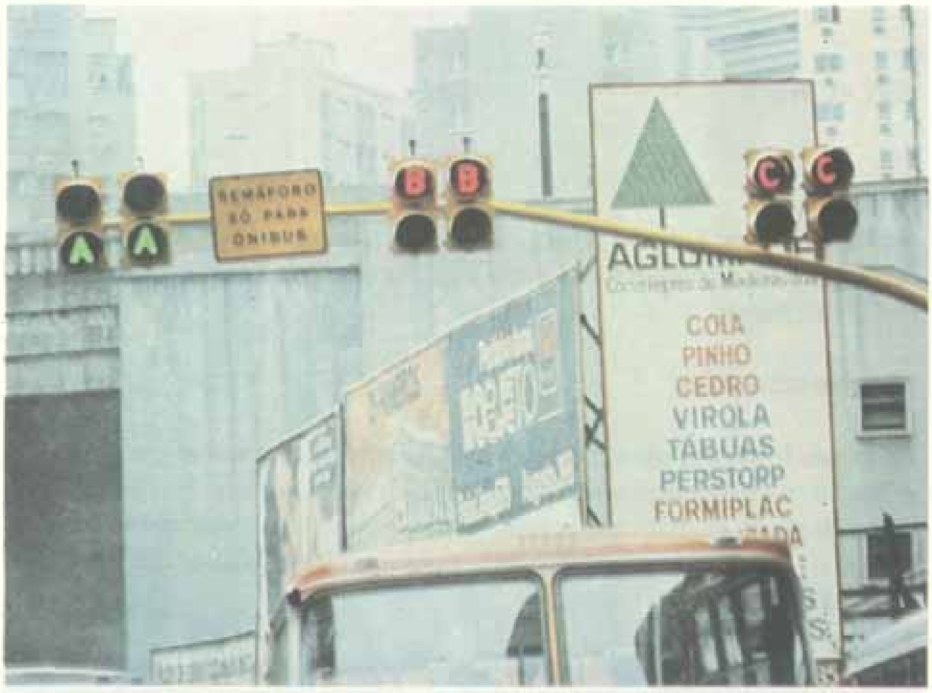
width of 20 m. At a point 120 m. beyond João Adolfo St., 9 de Julho Ave. tapers back to its normal width of 9 m. consisting of an exclusive bus lane of 3.60 m. and two automobile traffic lanes of 2.60 m. each. The location of the coordination station has sufficient width (see layout) to accomodate 3 bus lanes of 3 m. each, plus 2 lanes for autos.

For cars coming from Anhangabaú Ave. or Bandeiras Sq., no changes were required, except that 9 de Julho Ave. now has a transition from 4 to 2 lanes in a distance of about 100 m. less than before. However, cars coming from João Adolfo St. will have some difficulty to enter 9 de Julho Ave. since there is practically no space for merging. Buses leaving Bandeiras terminal have approximately 130 m. available to merge with through traffic and reach their respective lanes to begin the convoy.

COORDINATION STATION AT THE BEGINNING OF THE CORRIDOR

In each lane a letter corresponding to each bus group (A, B, C) was painted. After the stop line (6 m.) there is a traffic signal with 3 sets of signal heads, installed on a mast arm, each set located in front of the respective lane. Each set of signal heads consists of 4 faces of 30 cm. dia., 2 being red in case one of the lamps burn out, each containing their respective letters A, B or C. Also, at the beginning of the coordination lanes, there is a sign showing the color and letter of the group and the name of the corresponding bus companies.

Near the stop line is an elevated cabin where the traffic signal is operated manually. The signal operator, located in the cabin 3.5 m. above the ground, is capable of monitoring the buses leaving the terminal (170 m. in advance) up to the first bus stop (300 m. beyond the cabin). Furthermore, the traffic signal can also operate automatically in the following manner:



SIGNAL HEADS USED TO CONTROL BUS DEPARTURES

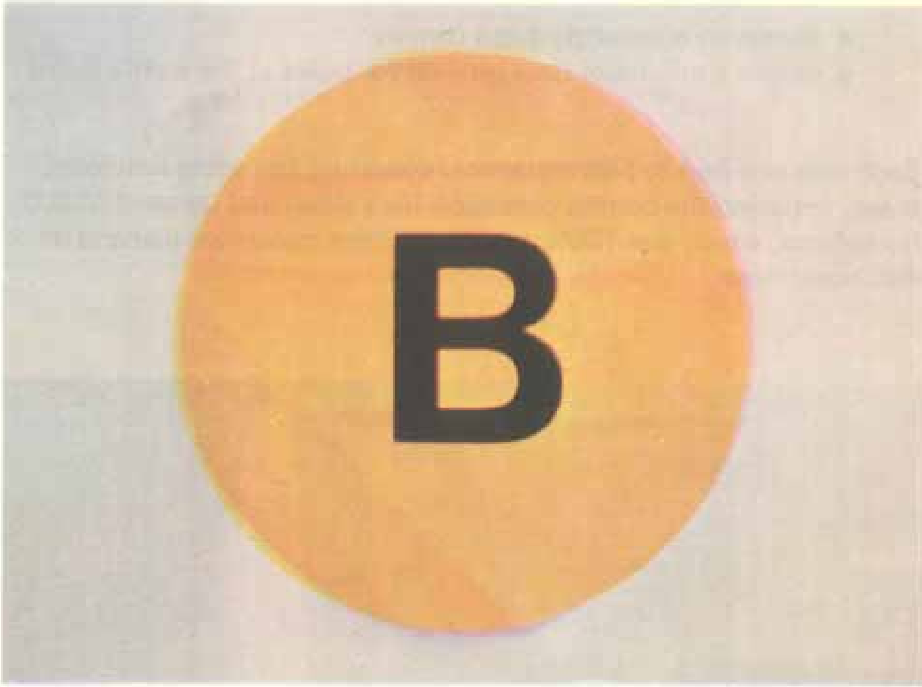
SIGNS SHOWING GROUP COLOR, LETTER AND COMPANY'S NAMES

Phase	Duration (sec.)
A	8
TOTAL RED	2
B	8
TOTAL RED	2
C	8
TOTAL RED	32
CYCLE	62

If phase A, B or C has a green indication, the other two corresponding sets of traffic signals are red until a phase change. Total red presents red on all heads.

Bus characteristics

All buses from the same company are placed in the same group in order to maintain uniformity of bus colors and groups. For easy identification, plastic decals with green, yellow and blue colors having letters A, B and C printed in black were made and placed on the front glass of the buses.



TRAINING

Driver and Supervisor training

DSV intended to train all bus drivers operating on 9 de Julho Ave. Due to lack of time and the large number of drivers, it was decided to train a portion of the drivers and all the supervisors and inspectors, who could then train the drivers. 350 drivers and 170 supervisors and inspectors were trained at 16 companies operating on the corridor. Training consisted of a general explanation of the project, its objective, and specific instruction of the principal requirements for a good COMONOR operation:

- use only the lane corresponding to your group (A, B or C);
- obey the control signal, observing the red indication. Maintain a limit of 2 buses from the same group each time;
- no passing on 9 de Julho Ave.;
- open doors only at the bus stop corresponding to the respective group;
- if possible, stop at the stop line;
- open the doors only once at each bus stop.

TRAINING THE TRAFFIC SIGNAL OPERATORS

Ten CET technicians were initially trained on the best way to operate the coordination station, trying to adapt the two conflicting objectives:

- obtain an adequately sized convoy
- obtain a minimum time interval for buses at the traffic signal

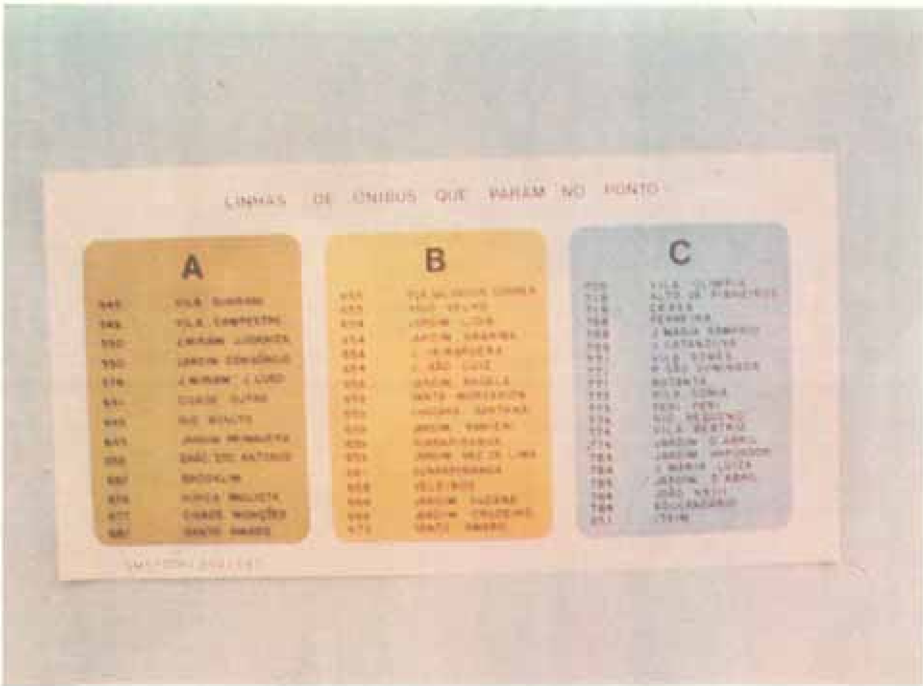
Each operator had to pass a practical operating test using simulated buses, requiring the correct operation for a simulated demand of 800 buses/hour, which was 100% over the current maximum demand of 400 buses/hour.

POLICEMAN INSIDE CABIN, OPERATING THE TRAFFIC SIGNAL

TRAINING OF BUS PATRONS

One week prior to project implementation, informational leaflets were distributed to people near the bus stops. In addition, extensive advertising in newspapers and on radio and TV was utilized.


AVENIDA 9 DE JULHO
"VEJA NAS PLACAS DE ORIENTAÇÃO EM QUAL DOS TRÊS PONTOS O SEU ÔNIBUS PARA"
C
B
A


LINHAS DE ÔNIBUS QUE PARAM NO PONTO
A
B
C

DISTRIBUTION OF LEAFLETS AT THE BUS STOPS

8
implementation

It was obvious after the third day of operation that the traffic flow had improved. However, various operational problems occurred during the first days which required additional supervision, orientation and inspection by several of the CET technicians.

COORDINATING STATION

The traffic signal operation presented no problems. Operators found the actual operation easier than they had expected while conducting the simulation experiments. Eighty percent of the bus drivers had no difficulties, even during their first trip and the remaining 20% easily learned the process after the second trip.

The major problem occurred with auto drivers who were confused by the traffic signal, despite the signs which had been installed with the message **"traffic signal for buses only"**, and insisted on waiting for the green light. It took about three weeks to accustom auto drivers to the traffic signal, principally because each day additional motorists passed the location who had not seen the signal operation since its installation.

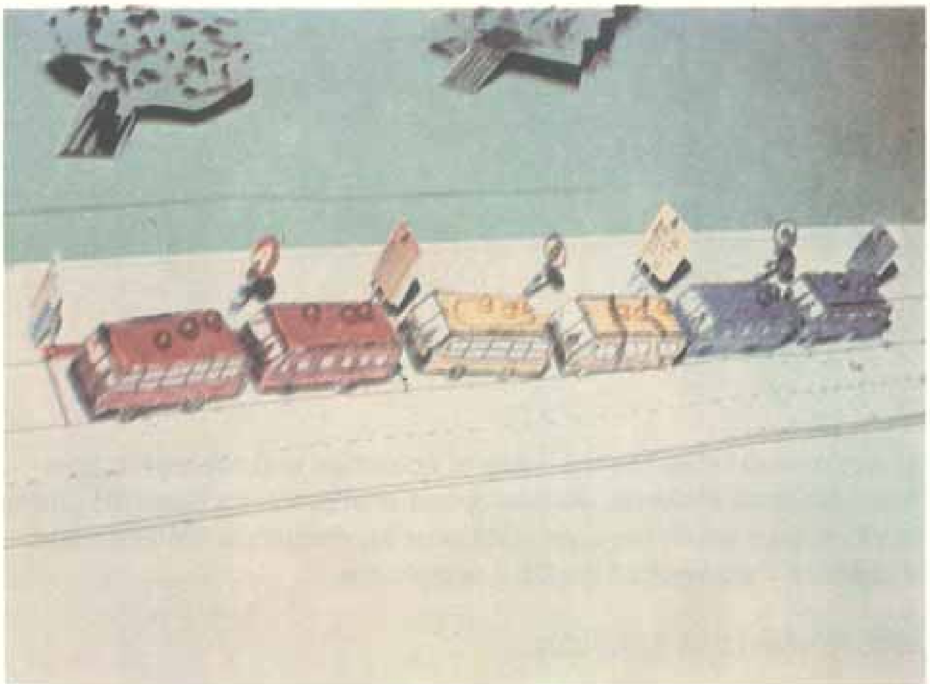
Traffic signal performance was practically the same as predicted during the simulations for both waiting time and the number of buses per convoy.

During off-peak periods, the traffic signal is being operated automatically on a fixed time cycle, with satisfactory results.

BUS STOPS

Bus stops were the major problem. Their performance, although sufficient to improve traffic flow, didn't reach 100% of the expected performance.

It was necessary to give orientation to passengers at the bus stops for one month after implementation, the time necessary for them to become accustomed to the system.



LAYOUT OF BUS STOP FOR CONVOY OPERATION

Bus drivers, in spite of the training and adequate traffic control, initially found it difficult to know where to stop, which resulted in delays on the arrivals and departures. Furthermore, being accustomed to stopping at the request of a pedestrian who signals him stop, the bus drivers would not advance to their proper position at the beginning of the sub-area, which impeded the other buses arriving in the convoy. To speed up arrival and departure performance, and to have drivers stop at the proper location, additional supervision and orientation had to be provided at the bus stops.

ALONG THE CORRIDOR

Approximately 8% of drivers did not respect the no-passing regulation, which slightly decreased the average size of convoy, and thus decreased the boarding efficiency at the bus stop.

BUS STOP WITH OPERATING CONVOY

To minimize these passing maneuvers, a control system was implemented which recorded the vehicle license plate at the beginning and end of the corridor. Passing violations could then be detected and warnings and/or fines given to the corresponding bus company.

EVALUATION OF RESULTS
(one month after implementation)

Although aware of the satisfaction of drivers, passengers and the general public for elimination of queues and improved stops, boarding conditions and general traffic flow, there had been no survey conducted related to public opinion.

BENEFITS

The main benefit noticed was reduced travel time along the corridor during the afternoon peak. Before the project, average travel time for the corridor was 24 minutes, and after was reduced to 13 minutes (a reduction of 11 minutes for the P.M. peak), and the average reduction in travel time for a total day was 4 minutes, which represents:

Investment savings

Eleven minutes saved during the peak hour signifies a fleet of 55 fewer buses than presently needed for the same capacity.

Bus hours

With a 4 minute economy per trip, for the 400 buses which travel the corridor each day, 266 bus hours are saved each day, or 80,000 hours annually, resulting in:

REDUCED OPERATING COSTS
AND FUEL SAVINGS

80,000 hours x 10 litres/hour = 800,000 litres diesel oil

SOCIAL COST REDUCTIONS

Personnel savings (driver and ticket collector)

80,000 x 2 = 160,000 hours

Passenger time reduction

80,000 hours x 30 passenger/bus = 2.4 million hours

SUMMARY OF BENEFITS

Investments	Cr$ 7.5 million
Operational Costs	Cr$ 5.6 million/year
Social Costs (measurable)	Cr$ 14.4 million/year
Annual total	Cr$ 27.5 million/year
	(US$ 1,800,000)

COSTS

Total costs for the project including traffic control, leaflets, training and supervision totalled approximately Cr$ 400,000.00.

PERSPECTIVES

Being considered efficient, operational and of low cost, the project will be extended to other corridors with similar problems. Future corridors to be studied will include Rangel Pestana—Celso Garcia Ave. and Radial Leste Ave. with 500 and 350 bus/hour respectively.

A series of experiments, analysis of performance levels, and simulations will be made on 9 de Julho Ave. to enable the preparation of a **COMONOR PROJECT CAPACITY MANUAL**, explaining the various conditions, where it can be implemented, and what are the advantages.

LONG TERM PERSPECTIVES

High densities

A coordinated bus convoy, in conjunction with exclusive lanes and other priority measures, permits a low cost, high capacity, and relatively high speed transport mode.

Figure 1 (pg. 28) shows the possibility of high capacity performance with large convoys, even with high density bus stops. On the 4 km. section of the 9 de Julho corridor, 12,000 passengers were transported on 300 buses/hour at 19 km/hour. The 13 minutes of travel time were spent as follows:

4 km. "free" trip time = 40 km/hour	6:00 minutes
at 5 traffic signals	1:70 minutes
at 6 bus stops	5:00 minutes
at coordination station	0:30 minutes
Total time	13:00 minutes

The project was implemented with practically no investment, and its performance could have been improved with low cost improvements such as exclusive central bus lanes; more intensive training and a bus actuated traffic signal. With these improvements, it may be possible to reduce the time from 13 to 9 minutes at a speed of 28 km/hour, which would be the practical limit for such high density traffic lanes.

Under these conditions, the number of vehicles could increase to 450 buses/hour in a convoy with a maximum of 8 buses, but averaging 6 buses/convoy, with an average occupancy of 60 passengers per bus and a maximum capacity of 27,000 passengers/hour. However, the city of São Paulo has only one transportation corridor that approaches such high demand (Rangel Pestana–Celso Garcia Ave.) and a metro line is now being constructed in this corridor which will create a modal split between metro and bus, thus reducing the existing high bus demand.

Low densities

At what level is the project advantageous for low density corridors?

In principle, whenever the time saved at the bus stops is greater to the time spent in organizing a convoy, the application of the convoy concept is valid:

a) when there is a bus stop with long queues with insufficient boarding capacity;

b) when the problem of long queues is not clearly identified but there is an increased delay during peak hours. In the case of exclusive lanes, this additional delay could be evaluated by differences in route travel time during peak hours compared with off peak travel time. As the minimum applicable limit for establishing a convoy, we have calculated for average conditions 140 buses/hour. A lower value would rarely present transportation problems which would justify a convoy solution. Furthermore, for lower demands, the time at the coordinating station increases too much.

9
appendices

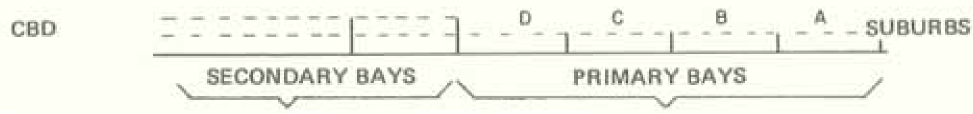
APPENDIX I

DESCRIPTION OF THE DIFFERENT POSSIBLE COORDINATION METHODS TRIED ON 9 DE JULHO AVE.

a) Initially we thought of using a radio system to inform bus drivers at the Bandeiras terminal when they could leave the terminal to form a convoy. However, with 52 bus lines, 2 of which did not pass through the Bandeiras terminal, it would require at least 6 persons and 6 radios. Therefore, the idea was abandoned.

b) Right after the Bandeiras Sq. exit, 9 de Julho Ave. is approximately 20 m. wide narrowing to 15 m. until it reaches João Adolfo St., where it widens again to a 20 m. width. About 120 m. beyond, it narrows again to its normal 9 m. width with a 3.60 m. bus lane and two 2.60 m. auto lanes, forming an excellent space for bus coordination.

At first it was decided to provide bus bays A, B, C, D, as needed, with sufficient space for each bus to enter.



In this manner, a C bus could be waiting in bay C, or an A bus could wait in bay A, until a coordinated convoy could be formed to begin the route together. If prior to convoy departure, one or more buses of the same group would arrive, they would wait in the secondary bay then move to the primary bay after the first convoy had left. However, since the buses do not arrive with precise regularity, it would have been necessary to release incomplete convoys to avoid queues in the secondary bays and to avoid excess waiting time, because the longer the convoy, the longer the waiting time.

To evaluate this inter-relationship, a simulation with different M values was made (M = number of line sub-groups) corresponding to the maximum convoy desired. Simulations showed (figure 2, pg. 65) that the larger the value of M, lesser is the waiting time needed to form an average n convoy (n = total buses + total convoy).

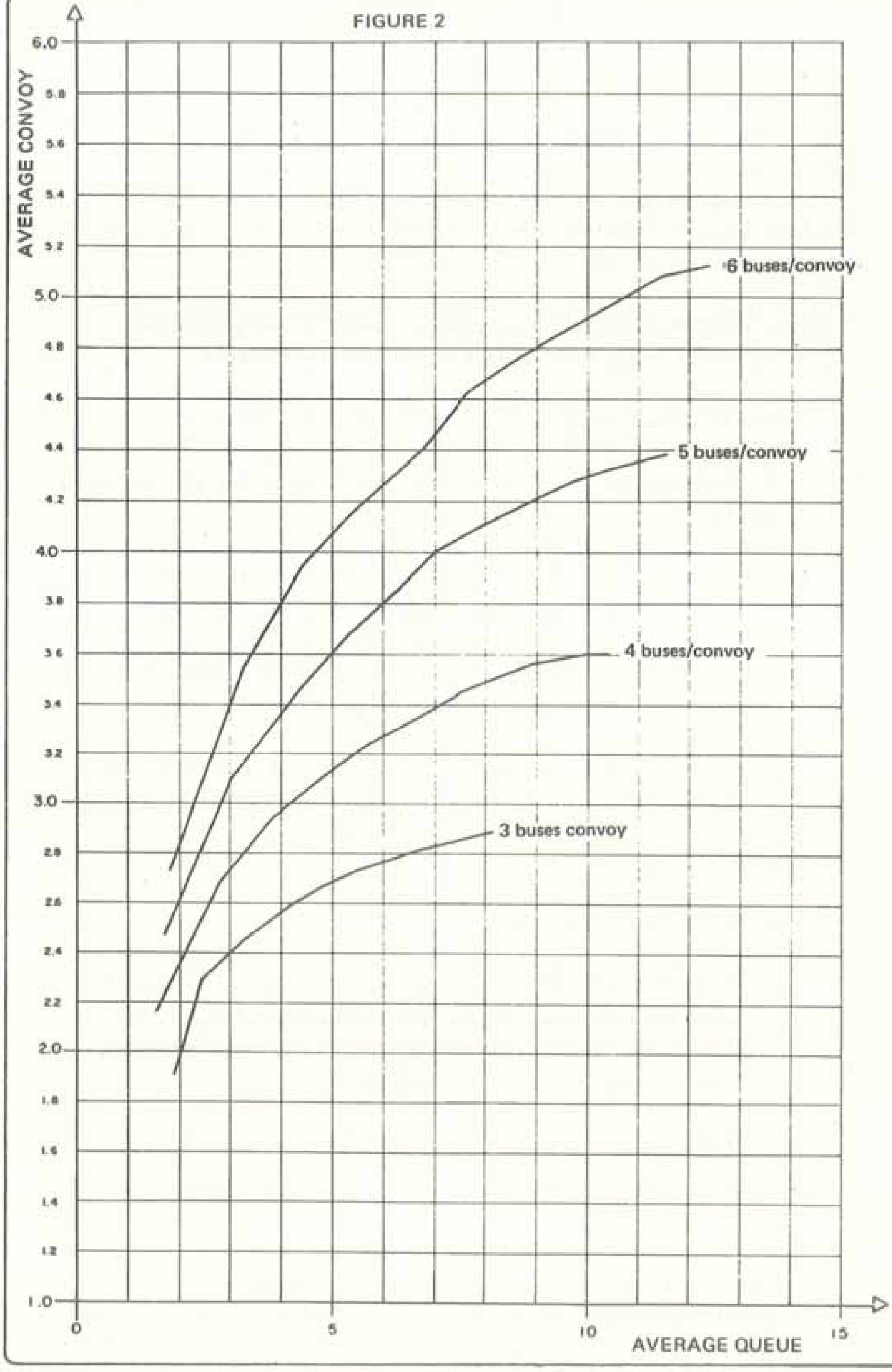
An example of the simulation results is shown in Appendix II (pg. 73) which illustrates the number of sub-groups (M) and the secondary bays (4). The simulation consisted of generating buses among the various groups and simulating solutions for both primary or secondary bays. A bus is released when the convoy is complete or when the secondary bays are full. Types of convoy released are shown in Appendix II.

Based on the results shown in Figure 2 it was decided to divide buses in 4 (M) groups considering that a number less than 4 would not form an average convoy (n) equal to or greater than 3. A number greater than 4 would complicate the convoy formation, plus requiring a larger area for its formation. Furthermore, it would be more difficult to divide it into uniform groups because of the large number of boarding passengers, bus companies and service areas.

After this division, different convoy formation methods were simulated:

- release convoys when the number of buses reaches 3
- release convoys on a fixed time interval

FIGURE 2


AVERAGE CONVOY
6.0
5.8
5.6
5.4
5.2
5.0
4.8
4.6
4.4
4.2
4.0
3.8
3.6
3.4
3.2
3.0
2.8
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0
5
10
15
AVERAGE QUEUE
6 buses/convoy
5 buses/convoy
4 buses/convoy
3 buses convoy

- although the bus order is "A", "B", "C", "D" don't wait to release bus "A" first, or wait for "B" if "A" has already left.

- if the last convoy could leave without a "D" bus, for example, don't wait for it before releasing the convoy.

In all, about 50 different methods were tried using 400 simulations, and the best method was chosen after consideration of the average waiting time for buses and the maximum convoy average (n). The method selected an average convoy (n) of 2.9 buses with a waiting time corresponding to the interval of arrival of 2.5 buses (approx. 30 seconds), while the simple method obtained only a 2-bus convoy in the same amount of time.

The coordination operation has, however, become more complex, requiring the following instructions to the **bus coordinator:**

a) verify to which group (A, B, C or D) the bus belongs in;

b) if the primary bay is full, orient the bus driver to his appropriate secondary bay;

   - if with this bus the total number of vehicles in the secondary bay does not accumulate to 3, wait for the next bus and release the convoy at the primary bay. After that, have buses in secondary bay move to the primary bay or release them immediately, depending on the analysis of the following factors:

c) if the primary bay is empty (either for a bus just arriving or for those in the secondary bay after convoy departure) verify if the bay is empty (free) or if it is a reserved bay (from where a bus has departed previously);

   - if it is empty (free) verify:

     – if it belongs to group A, observe if the last convoy has left with a D bus. If so, release bus A and reserve its bay. If there is a bus B it can be released and its bay reserved. If not, direct the bus to its corresponding bay;

     – if it is a B, C or D bus, verify next bay respectively A, B or C;

   - if it is reserved, release the bus just arriving and reserve the bay;

   - if it is empty, verify if this bus is the one in sequence to the last bus of last convoy. If so, release it so it can catch up to and become a part of the last convoy. If not, position it in its bay.

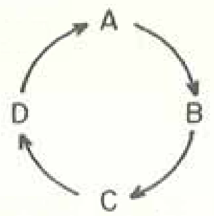
- if it is a reserved bay, position the bus in the secondary bay.

d) everytime that the number of buses in the primary bay, plus those in the secondary bays, is equal to or greater than three, release the convoy.

As can be seen, this "efficient" method would require one or more 'supermen' to operate the "Coordination Station".

ROTATING ORDER

In an effort to simplify the formation method, a rotation scheme was studied. In this scheme, there would be no need to form A, B, C, D convoys for release but simply maintain the order:

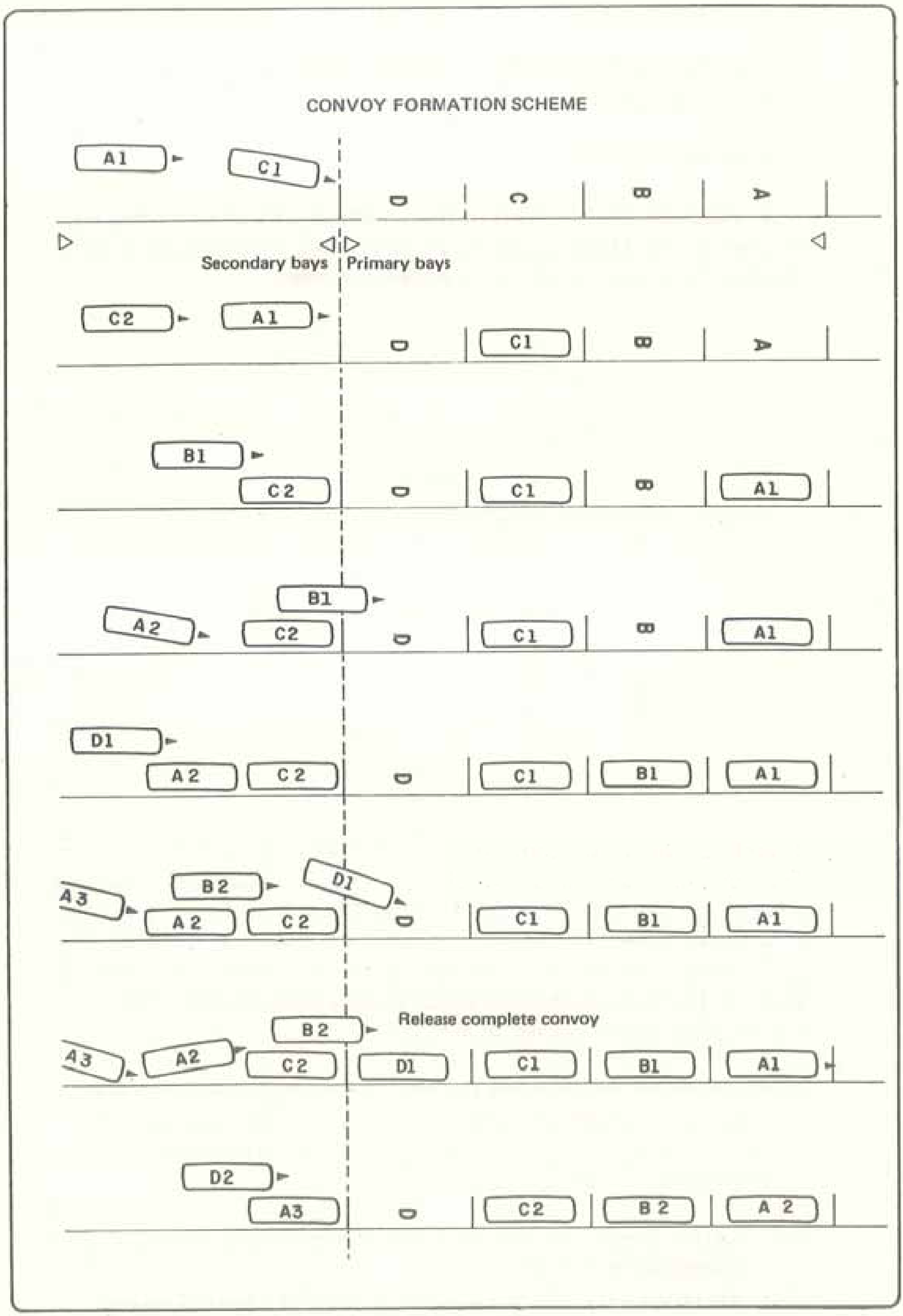


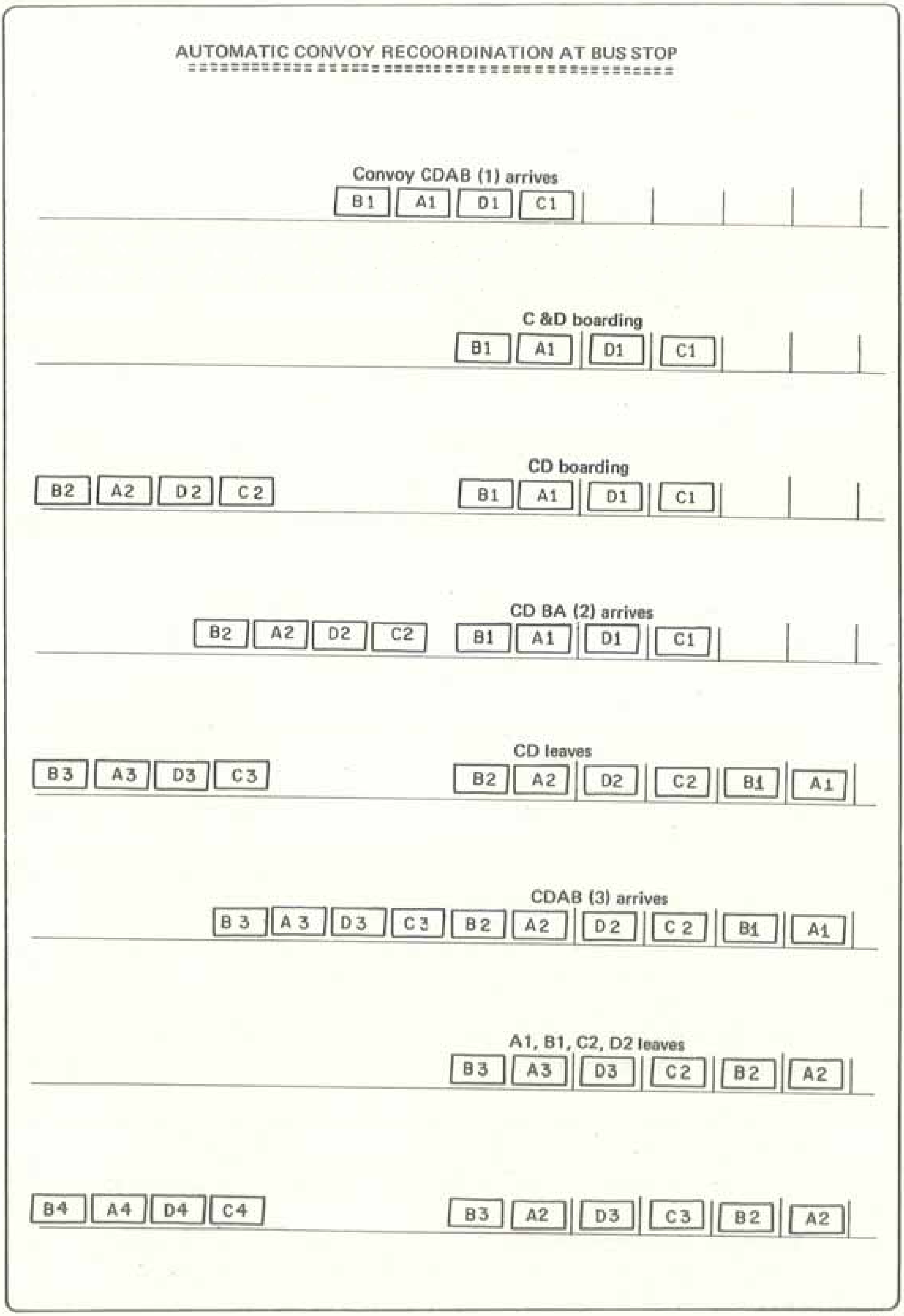
Therefore, even if two convoys departed like CDAB, CDAB, after the first bus stop buses C and D would stop in their sub-areas for boarding and unboarding, while A and B would simply stop and wait for C and D to depart. When A and B would reach their respective sub-areas for boarding and unboarding, in probability the following convoy (with C and D in front) could reach A and B, thus forming for the remaining trip length a normal convoy of ABCD.

If no congestion occurs at the bus stop, there would also be no need of a convoy. If congestion occurs, then buses can group again in the sub-areas in order of A B C D, to attain the maximum capacity. In this rotation scheme, there are always two variables:

F = waiting queue – the total number of buses in any one group waiting to be released;

P = the probability of a bus entering in front of a waiting queue.


CONVOY FORMATION SCHEME
Secondary bays
Primary bays
Release complete convoy
A1
B1
C1
D1
A2
B2
C2
D2
A3
A
B
C
D


AUTOMATIC CONVOY RECOORDINATION AT BUS STOP
Convoy CDAB (1) arrives
B1 A1 D1 C1
C &D boarding
B1 A1 D1 C1
CD boarding
B2 A2 D2 C2
B1 A1 D1 C1
CD BA (2) arrives
B2 A2 D2 C2 B1 A1 D1 C1
CD leaves
B3 A3 D3 C3
B2 A2 D2 C2 B1 A1
CDAB (3) arrives
B3 A3 D3 C3 B2 A2 D2 C2 B1 A1
A1, B1, C2, D2 leaves
B3 A3 D3 C2 B2 A2
B4 A4 D4 C4
B3 A2 D3 C3 B2 A2

EXAMPLE:

Bus in line	Last bus released	Buses that can enter in front of waiting line	P	F	P/F
A DDD CC	A	B	1/4	6	0,0416
C A	C	D, B	1/2	2	0,25
AAA	A	B, C, D	3/4	3	0,25
BAA	B	C, D	2/4	3	0,166
D	D	A, B, C	3/4	1	0,75

We have thus defined the following method: to release one or more buses in order A, B, C, D, A, B, C, D ... always when the P/F relationship becomes less than a given constant.

The convoy rotation system was simulated for different P/F relations (entrance probability/waiting queue) and the results were plotted on the enclosed table and graphic.

For high P/F volumes, better results were obtained than for any prior methods. For low P/F (long waiting times, more complete convoys), results were practically equal to those of the previous best methods. However, the proposed method presents an additional difficulty: the lack of a determined position for each bus, whose location in the bay (primary or secondary) should be variable, complicates the operation both for bus drivers and the convoy coordinator. To facilitate the operation a storage sequence plan was tested as illustrated.

There would be 3 bus lanes, 2 of which would accumulate buses to be released when necessary. The third lane (to the right) would serve buses that, according to arrival sequence, would not be separated.

Example: If we imagine that D was the last bus to leave, and after it arrived buses in order C, B, D, C, A, B, B, D, A, they would be accumulated as follows:

1	2	3	4	5
C	C	D C	D C	D C
	B	B	C B	C B
				A

(in 5 above an ABCD convoy would be released, leaving a C bus)

5	6	7	8	9
	B	B B	B B	B B
C	C	C	D C	D C
				A

(in 9 above another convoy would be released, leaving a B bus)

This method should use 2 operators:the first one would distribute buses on X and Y lanes or let them just go, while the second would release buses on X and Y lanes so as to obtain a convoy in the right order.

Because there exists 3 lanes and 4 bus groups, the average convoy efficiency would be reduced. Therefore, if buses arrived on a D, C, B order, the D bus would enter X, bus C in Y, and bus B would pass both to go directly in front without waiting for bus A and would form a 3-bus convoy.

In spite of these disadvantages, simulation results were almost as good as those of the previously explained rotation method.

Although feasible, the operational scheme was complicated, requiring fast coordination between both operators, as well as cooperation from the drivers.

DOUBLE SEQUENCE

To improve project operation, the original plan was again modified:

1) three groups were formed instead of 4 where João Adolfo St. is sufficiently wide to permit the utilization of 3 exclusive lanes, thus allowing all buses from the 3 (A, B and C groups) to go directly to their lanes, eliminating the need for the first operator and making it easier for the driver;

2) these 3 lanes could be controlled by a manual or automatic traffic signal, with fixed cycle, with a green indication to one lane at a time. Considering that there is a lane for each group, the control operation is much easier than for the other methods;

3) to compensate for the reduction from 4 to 3 groups, 2 buses of the same group could form a line in convoy. With this operation, a complete convoy was changed from 4 vehicles (ABCD), to a maximum of 6 (AA, BB, CC);

4) Each sub-area at the bus stops would then have 1 or 2 buses from each group, 22 m. instead of 11 m., totalling 66 m. instead of 44 m. per bus stop. Delay in boarding for the users will be small, since during the peak hour a large number of passengers will not be concentrated at the door of one bus.

   In the case of ABCD, presuming that passengers would be uniformely spread alongside 11 m. of the sub-area, they would have to walk approximately 2.75 m. to reach the bus door.

   For the double sequence method (AA, BB, CC), presuming that passengers will be uniformely spread along 22 m. they will walk an average of 9 m. or 4.15 metres more. This represents, potentially, 4 extra seconds to board a convoy, but the convoy can also potentially increase from 4 to 6 buses, thus compensating this loss.

Simulations made for the actual order in which buses leave (checked for 2 peak hours) indicated an average queue of 1.66 buses (which represents an average delay of 20 sec/bus), permitting an average convoy of 4.6 buses which is a higher rate than the one obtained in the previous method.

The double sequence system was definitely chosen because it permits a substantially easier operation, decreases waiting time, and increases the average convoy (n).

The AA, BB, CC convoy was detailed in a series of simulations, both for convoy formation and boarding and unboarding operation at bus stops, and a small model to demonstrate coordination and boarding processes was developed.

The project was submitted for final approval in July/August of 1977, at which time it was decided to implement a pilot-plan on the 9 de Julho Ave. corridor.

APPENDIX II

COMPUTER SIMULATIONS AND CALCULATIONS

To support the project concept, a series of computer simulations and calculations were made to obtain greater safety and accuracy to the feasibility studies and project design.

COORDINATION STATION

Division in different groups

Normally, the buses of the different groups don't arrive with the same frequency, requiring a convoy to depart incomplete, or else waiting time substantially increases.

Therefore, it was necessary to adopt a criteria to release incomplete convoys. The easiest way would be to release it every time that waiting lines would reach a certain length. The greater the waiting time, the greater is the probability for an average convoy to approach its maximum, having a cume of coincidence for this value.

Simulation was used to determine the average medium convoy curves, in function to waiting time for subdivision in the different balanced groups, from 3 to 6.

Figure 2 (pg. 65) illustrates these curves.

DIFFERENT RELEASING METHODS

With 4 sub-groups, which was considered the best division at first, 50 different simulations were made using 400 situations. Some of the findings are shown in the graphic.

Variations in the methods consisted, for example, in releasing buses in front first, or release buses which will complete a convoy previously released, or even analyze the waiting queues of the different groups to determine convoy departure.

ROTATING METHOD

This method neglects the convoy idea, and tries only to maintain an ABCDABCD order. This coordination scheme shows that an optimum method would be to verify the coefficient K which equals the number of spaces/number of buses in front and releases the convoy everytime there is a coefficient which reaches a certain limit.

ROTATING METHOD WITH DOUBLE SEQUENCE

This method was chosen and implemented with 3 sub-groups (A, B and C), because it presented more adequate conditions for the existing corridors. Therefore, a series of simulations were made with different P/F relations, where:

P = probability of a bus entering in front of those in the waiting queue

F = total buses in the queue

EXAMPLE:

Buses in the queue	Last bus released	Buses that may enter in front of the bus queue	P	F	K P/F
A BB	C1	C(2) A(2)	2/3	3	0,222
A AB	C1	C(2)	1/3	3	0,111
A BB	C2	A(2)	1/3	3	0,111
CC	C2	A(1 ou 2) B(1 ou 2)	2/3	2	0,333

The criteria consisted of always releasing a bus when the P/F reached an inferior value to a determined limit (K1). The lower the value of K1, the larger are the bus queues and average convoys. The figure and graphic illustrate the results.

Furthermore, an automatic operation with a fixed cycle was simulated, using different cycles, and corresponding convoys and waiting times were obtained.

Simulations were run using dependent bus generation factors, and for actually observed frequencies for 2 hours in the afternoon peak. The results were nearly the same.

BUS STOP SIMULATIONS AND STATISTICS

Boarding distribution calculation

At first, to make a general check of the capacity beginning with passenger demand for each line, calculations were made to verify the average maximum of passengers for a given convoy, as well as its standard deviation.

Results were obtained by using the following empirical formula:

$$t = \frac{6}{2 + n}$$

which shows how the average boarding time per passenger decreases (t) in function to the average convoy (n).

Convoy simulation

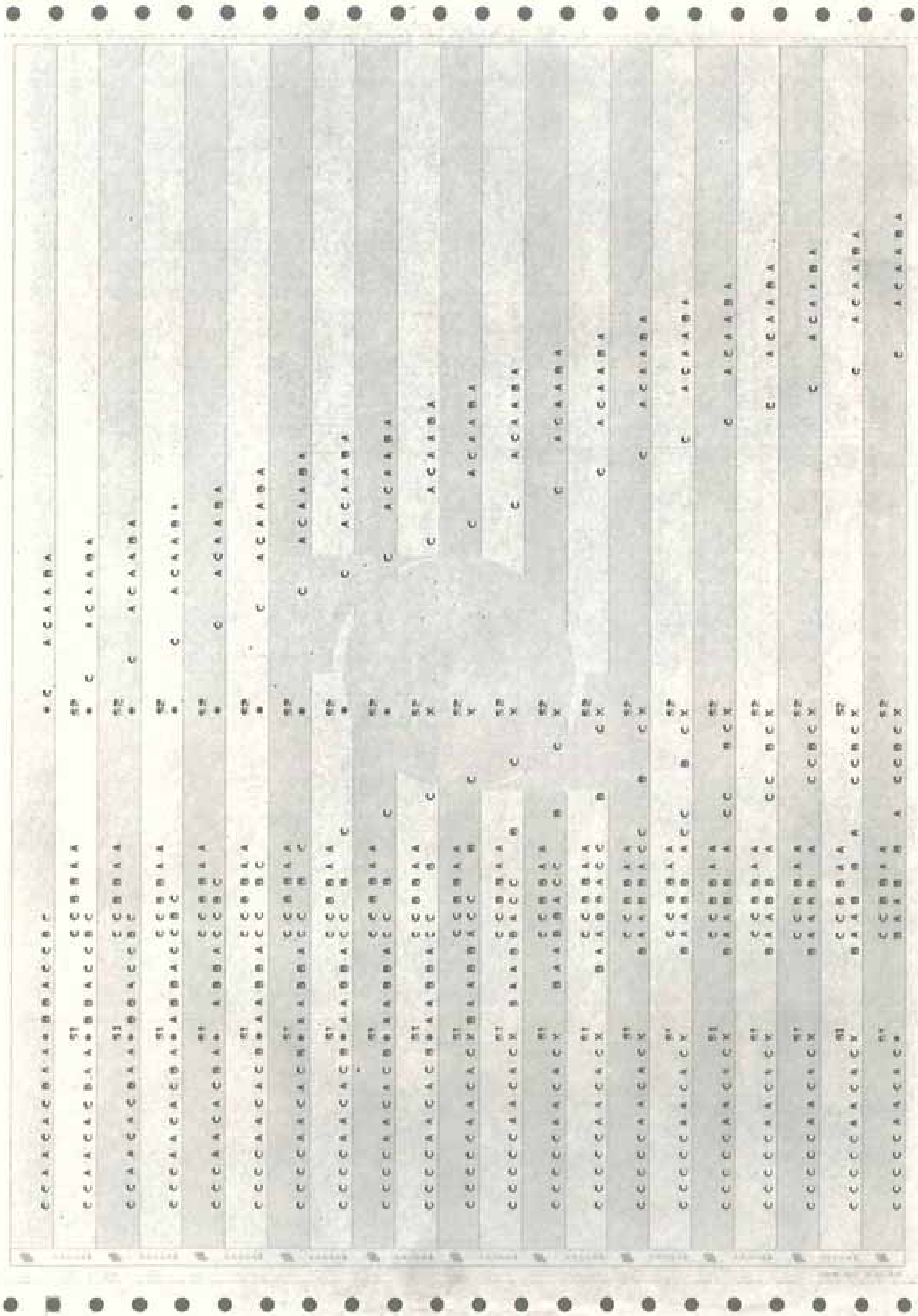
For a more realistic simulation of bus stop efficiency, situations with the following characteristics were developed:

- inclusion of traffic signals before and after the bus stops, with cycles, offsets and green time;
- dependent factor generation of the number of boarding passengers for each bus, dividing the average demand for each line;
- variations in bus frequency, bus stop location and passenger demand;
- simulation of operations for stops and departures near traffic signals, and passenger boarding and unboarding near the bus stops.

This program was integrated with the coordination station simulator which made it possible to verify the capacity and performance of the system under different conditions, varying bus volumes, passenger volumes, coordination policy, bus stop locations, signal cycles, percentage of green time and signal offsets.

We were then able to establish the best parameters to optimize the performance during different hours of the day.

```
C.E.T. - COMPANHIA DE ENGENHARIA DE TRAFEGO          S E T  - C T  - DEPARTAMENTO DE ESTRATEGIA E CONTROLE
--------------------------------------------------   -----------------------------------------------------

                                          P R O J E T O   C O M O N O R
                                          -----------------------------

                    SIMULACAO P/ FORMACAO DE COMBOIOS DE ONIBUS E P/ PONTOS DE ONIBUS ENTRE SEMAFOROS
                    ---------------------------------------------------------------------------------

     TOTAL DE ONIBUS SIMULADOS =  467
     -------------------------

     FATOR DE CARGA DE PASSAGEIROS = 1.00
     -----------------------------
     TOTAL DE VAGAS ENTRE OS DOIS SEMAFOROS =   15
     --------------------------------------

     NUMERO DE VAGAS ENTRE O SEMAFORO ANTERIOR AOS PONTOS DE ONIBUS (S1) =   5
     -------------------------------------------------------------------

     NUMERO DE VAGAS ENTRE O PONTO DE ONIBUS E O SEMAFORO POSTERIOR (S2) =   7
     -------------------------------------------------------------------

     DEFASAGEM PERCENTUAL ENTRE OS SEMAFOROS = 0.5
     ---------------------------------------

     TEMPO DE CICLO =120
     --------------

     PORCENTAGEM DE VERDE DO SEMAFORO  S1 = 0.70
     ----------------------------------

     PORCENTAGEM DE VERDE DO SEMAFORO  S2 = 0.62
     ----------------------------------

     POSICAO DOS PONTOS DE ONIBUS =CCBBA
     ----------------------------
```



SIMULACAO PARA PONTO DE ONIBUS ENTRE DOIS SEMAFOROS

NUMERO DE VAGAS PARA ONIBUS ENTRE OS SEMAFOROS = 18   POSICAO DOS PONTOS = CCBBAA

PORCENTAGEM DE VERDE PARA O SEMAFORO ANTERIOR AO PONTO = 0.70 PORCENTAGEM DE VERDE PARA O SEMAFORO POSTERIOR AO PONTO = 0.62

DEFASAGEM PERCENTUAL DO CICLO = 0.0   FATOR DE CARGA DE PASSAGEIRO = 1

CICLO	X 12	11	10	9	8	7	6	5	4	3	2	1	0
	Y 0	1	2	3	4	5	6	7	8	9	10	11	12
14	263	207	316	344	374	379	380	384	377	357	325	308	292
16	263	279	301	335	364	375	383	384	376	364	349	336	288
18	284	293	329	343	363	376	376	381	376	359	343	330	287
20	277	299	314	334	362	366	374	374	368	351	344	325	286
22	273	285	311	329	334	367	368	367	367	360	347	341	303
24	281	293	312	324	337	348	357	363	368	349	343	336	294
26	290	310	314	334	352	352	356	361	365	351	331	332	305
28	287	295	304	328	336	347	349	358	357	339	318	307	289
30	278	281	296	305	326	340	353	351	349	333	317	297	281
32	261	269	277	300	328	336	350	341	345	337	315	304	279
34	264	274	287	294	330	343	352	348	341	337	310	302	268
36	259	271	280	301	323	342	346	343	340	335	323	315	279
38	260	276	287	292	315	328	325	332	335	334	317	306	277
40	262	267	287	294	310	316	318	328	330	327	319	308	278

COEF. FL	N. MED. ONIB. P/ COMB.	TEMPO MEDIO ESPERA
3.000	1.593	0.0
2.000	1.898	0.253
1.500	2.104	0.476
1.000	2.240	0.573
0.750	2.670	1.099
0.666	2.826	1.381
0.600	2.826	1.381
0.500	2.826	1.381
0.428	3.057	1.635
0.400	3.257	1.675
0.375	3.076	2.076
0.333	3.262	2.543
0.300	3.262	2.543
0.285	3.262	2.716
0.270	3.262	2.716

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Transyt — no prelo

Controlador de Semáforos
Atuados pelo Tráfego:
projeto e execução — no prelo