MOBILITY AIDS FOR THE SEVERELY HANDICAPPED
A STATUS REPORT

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1. INTRODUCTION

To achieve any measure of independent mobility, all quadriplegic and some paraplegic patients must use powered wheelchairs. These patients are forced to accept the limited performance of their wheelchairs in any but ideal surroundings; a steep grade or rough terrain becomes an impassable barrier. For independent long-distance travel, most of these patients use specially adapted vans and automobiles. When attempting to drive such licensed vehicles, they find that hand controls often prove inadequate and unsafe. Further, since transfer to automotive seating is at best inconvenient for paraplegics and impossible for quadriplegics without assistance, they must sit in their wheelchairs which lack adequate structural strength for automotive seating and which may be improperly fastened to the vehicle. This situation is hazardous and violates Department of Transportation (DOT) seat restraint regulations. Obviously, there is a need for safe, dependable, transportation systems for the handicapped which overcome these problems.

With these failures of existing transportation systems to meet the needs of the neuromuscularly handicapped so evident, Mobility Engineering and Developement (MED), Inc., in 1966 began the development of safe and efficient wheelchair and automotive van (chair-van) transportation systems. To date, MED has developed and is marketing chair-van systems which meet most of the needs of the group of

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a This work was performed under VA Contract V101 (134) P-173. Work will continue under VA Contract V101 (134) P-482.

b These systems have been developed over the last 10 years by MED, Inc., without outside funds. The systems are described in Section 2 of this report.
neuromuscularly handicapped who have a certain degree of muscle power and range of motion (at least in one arm) as well as reasonable eye-to-hand coordination. A wheelchair and powered driver’s seat which can be safely and reliably restrained in the van is currently being developed for use with these systems. MED, Inc., is conducting further research to develop more sophisticated transportation systems to provide independent mobility for an even larger group of the severely disabled.

2. DESCRIPTION OF THE “MOBILITY 3000” SERIES CHAIR-VAN SYSTEMS

The Mobility 3000 Series chair-vans are the result of 10 years of research, and have undergone considerable development from their predecessors. They place safe, independent mobility within reach of a substantial number of quadriplegics who were either unsafe or marginal when trying to use adaptive hand controls. The 3000 Series chair-van systems meet the needs of most quadriplegic drivers who have limited power and range of motion, and who possess reasonable eye-to-hand coordination.

The 3000 Series systems have four major component parts: (i) a van-compatible wheelchair (powered driver’s seat), (ii) a commercially available automotive type van, (iii) a commercially available elevator-lift for independent wheelchair entry and exit from the van, and (iv) a van control, instrumentation, and adaptation package to interface the van with the wheelchair and patient. This package includes a single floor-mounted control column, easily reached by the patient, which provides servosteering and control of the brakes and the throttle.

Forward motion of the control column actuates the throttle; rotation of the 9-inch-diameter semicircular steering wheel on the control column through ±90 deg steers the vehicle; and moving the control column to the rear, toward the driver, applies the brakes (Fig. 1). The maximum force required in any direction is 6 oz. Range of motion

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* The development of this van-compatible wheelchair is being done under contract to the Veterans Administration (Contract V101(134) P-173). The chair is described in Section 4 of this report.

* Development of these high-reliability systems is being done under contract to the Veterans Administration (Contract V101 (134) P-173). The systems are described in Section 5 of this report.

* Early versions of Mobility Chair-Van Systems have been described briefly by Scott (1).

* 1975 or newer Ford Econoline E-150, with power brakes, power steering, 300 or 351 in³ engine; other makes and models are adaptable on a custom basis.
fore-and-aft is 4 to 6 in. The control column is statically balanced to eliminate reaction to acceleration and braking forces. Handgrips of various types can be provided to adapt the control column to a patient’s particular needs.

![Floor-mounted control column.](image)

The steering control is hydraulic, and employs the van’s original power steering pump in a modified form as a primary source. In addition, an electrically driven pump provides steering assist in the event of a primary system failure. The emergency pump is automatically actuated, though there is provision for manual actuation by the driver.

The brake system is a vacuum-powered booster system in dual tandem. Each system has an independent vacuum reservoir. Either booster is sufficient to provide powered braking, though the required control forces increase slightly if either booster fails. If the vacuum source fails,
the vacuum reservoirs store enough vacuum for approximately 15 applications of the brakes.

Since it is difficult, if not impossible, for a quadriplegic to manipulate standard automotive instrument panel controls, all driving and environmental controls are contained in a single control box within easy reach of the driver (Fig. 2). Each control is operated by activation of an illuminated pushbutton switch requiring less than 8 oz of momentary force. The van ignition, gearshift, lights, turn signals, windshield wipers, horn, etc. are among these controls. A steering-wheel-mounted auxiliary control box also is available, for drivers with control capabilities remaining in only one upper limb (Fig. 3). This auxiliary control box rotates with the steering wheel, thus enabling the driver to operate all controls on the box without removing his hand from the steering wheel. In this way, the driver can shift gears while maintaining brakes, operate the horn or dimmers while steering, etc.

A van-compatible wheelchair must meet the nonlicensed mobility aid needs of the independent quadriplegic driver, in addition to the van-compatibility and safety requirements. Unfortunately, no commercially available wheelchair does so, adequately. As an interim solution, MED, Inc., has been using modified versions of several commercially available powered wheelchairs. MED, Inc., has found the Wheelchairs, Inc., adjustable-height powered wheelchair to be the most suitable (Fig. 4). In MED's modified version, the elevating base of this wheelchair is retained but the original seat is replaced with a contour-molded fiberglass-reinforced seat which is attached to the base with a special high-strength chrome molybdenum tubing interstructure, to permit loads to be taken
from the seat directly to the van floor structure. A special hold-down assembly with rear access, and an electrically operated lock, secure the chair to the van. Bilateral shoulder restraints and a lap safety belt attach to the interstructure. Flip-up armrests and an articulated footrest complete the wheelchair modifications. This interim seating arrangement does provide adequate headroom and safe seat restraint, but many of
the needs of the independent quadriplegic driver are not met. For this reason, MED, Inc., in 1973 began development of the van-compatible wheelchair described later.

Recent work with spinal-cord-injured patients has led to the development of special adaptations of the basic system. These adaptations, in conjunction with modified orthotic devices for wrist and finger stabilization, have been successful in permitting safe driving control by patients without tactile sensation or finger control (Fig. 5).

### 3. Powered Wheelchair for the Independent Quadriplegic Patient

**A. Background Discussion of Powered Wheelchairs**

Independent mobility for quadriplegics as well as some paraplegics almost invariably involves some type of electrically powered wheelchair. Until rather recently, the powered wheelchair used by most patients was the Everest and Jennings “34” Power Drive. Several other types of powered wheelchairs are now available from Everest and Jennings, as well as from other companies such as Motorette, Rolls Electric Wheelchair, A–BEC, and Wheelchairs, Inc. Drive assemblies vary, though most employ belt drives or direct friction drives.

Control is usually achieved by using a fingertip-actuated joystick. Pushing the joystick forward moves the chair forward, pulling the joystick back moves the chair backward, and pushing the joystick left or right turns it in the respective direction. Other types of controls are available for more severely involved patients who are generally unable to use manual joystick controls. Lipskin (2,3) describes chin-controlled joysticks, sight switches, and breath controls. Lozac'h et al (4) discuss a head control for quadriplegics.

For patients confined to the immediate physical environment of the home or hospital, many of the commercially available electric wheelchairs are satisfactory. But many patients refuse such confinement and seek an active role in society, returning to work or school. In so doing, these individuals must negotiate rough and uneven terrain as well as steep inclines. Distances to be traveled by wheelchair on a single battery charge are sometimes as great as a few miles. Speed often becomes a critical factor, especially if entering into traffic and crossing at busy intersections is required. The use of a licensed vehicle (automobile or van) to transport the patient and his wheelchair over large distances to work, school, etc. becomes necessary, and with it the requirement that the wheelchair be compatible with the licensed vehicle. Thus, as the quadriplegic patient ventures away from the protective environment of the home or hospital, his need for increased performance from his...
As a result, the conventional electrically powered wheelchair is undergoing a metamorphosis into a high-performing nonlicensed vehicle. At this time, no commercially available wheelchair meets the needs of the quadriplegic or severely neuromuscularly involved patient desiring true independence.

B. Design Criteria for Nonlicensed Mobility Aid (Wheelchair)

Several researchers have published information concerning the non-licensed mobility aid needs of the severely handicapped: Lipskin (2), Bray (5), Bray and Cunningham (6), Anderson (7), Cunningham (8), and Scott (1). The following list of design criteria for wheelchairs for the severely disabled, compiled from these and other sources, is felt to be necessary and sufficient in most cases for independent short-range mobility (wheelchair) and for independent long-range mobility (chair-
van systems). It is presented in what is felt to be the order of importance.

1. Powered height-adjustment, controlled by the user: this is needed to achieve head clearance inside the van where headroom is about 50 in. floor-to-ceiling.
2. Structural integrity: the wheelchair when mated to the van must meet the minimum Department of Transportation restraint requirements (20g seat; 40g seat and driver).
3. Headrest provisions: the head should be supported to prevent whiplash injuries of the cervical spine.
4. Hip and torso lateral support with adjustment, including bilateral shoulder restraints and a lap safetybelt: needed for comfortable posture control to maintain the patient in the correct driving position, and for safety.
5. Overall good posture control with adequate weight-distribution characteristics, to prevent tissue trauma and decubitis ulceration.
6. Selection of sizes and adjustments, with adjustment variation or selection encompassing 90th percentile of the adult population.
7. Rough, uneven, and inclined terrain stability, achieved by (or equal to that resulting from) positive power steering of one or both front wheels.
8. Controls with activation forces not to exceed 8 oz and consistent with accepted human factors principles.
9. Good vehicle stability at all seat height positions, achieved by a low center of gravity in the lowered position and by acceleration, speed, and inclination limiters in the raised position.
10. No obstructions to lateral body transfer on either side of the seat.
11. Relatively soft ride with excellent accommodation for rough or uneven terrain.
12. High durability and reliability.
13. Parking brakes, for use while transferring and for safety on steep inclines.
14. Modular design, to facilitate servicing by semiskilled personnel.
15. Reverse speed limiter.
16. Automatic variation of power steering as a function of speed.
17. Cruising radius per-battery-charge in excess of 3 mi.
18. Automatic recharging of wheelchair battery (or batteries) from the van electrical system and from any 120V a.c. 60 Hz outlet.
19. Top speed of approximately 10 m/h.
20. A 20 percent grade hill-climbing ability.
21. Indoor maneuverability equal to, or nearly equal to, that of a conventional wheelchair—plus capabilities for:
   a. Close frontal approach to a vertical wall or barrier;
   b. Passing through a 22 in wide doorway;
   c. Turning around in a 40 in corridor.
22. Low force requirements for pushing by an attendant in the event of a malfunction.
23. Overall light weight.
24. Parking lights, headlights, and turn signals, for safety at night.
25. Warning bell or horn.
26. Electronic combination lock, operable by the patient and/or attendant to minimize theft of an unattended wheelchair.
27. Instrument panel, including status and failure indicators (e.g., battery charge remaining, parking brake set, chair fully lowered, speed being limited, speedometer, odometer, radio).
28. CB radio, to summon aid.
29. Special control panel, for use by attendants.
30. Full leg and back extension (e.g., recline) in at least one position, for resting and overall body weight distribution.
31. A 12–in curb climbing capability.

No wheelchair currently meets more than about 16 of these criteria. The best commercial wheelchair meets only 10 or 12. For use in a chair-van system, a wheelchair should meet at least the first 18 criteria. In addition, the chair should possess a top speed of at least 4 m/h and the ability to negotiate a 10 percent grade (reduced version of criteria 19 and 20). Indoor maneuverability (criterion 21) can be somewhat relaxed if transfer to a conventional wheelchair is possible at home or at other frequented locations. The remaining specifications should be met if possible but are of an optional nature depending upon individual patient requirements.

4. COMPREHENSIVE PROGRESS REPORT:
THE MOBILITY VAN-COMPATIBLE WHEELCHAIR
JULY 1, 1973 THROUGH SEPTEMBER 30, 1976

A. Basic Description

On July 1, 1973, MED, Inc. began the design and development of a van-compatible wheelchair and powered drivers seat, meeting nearly all of the design criteria listed in the preceding section. The chair will feature continuously variable control of the wheelchair speed in both the forward and reverse directions, positive power steering, automatic control of relative drive wheel speed as a function of steering, and automatic variation of power steering ratio as a function of speed. The variable height chair will possess an extra long wheelbase in its lowered position for increased stability in high speed operation (Fig. 6). As the height is increased the wheelbase will decrease, thereby improving indoor maneuverability (Fig. 7). Van-compatibility is achieved by use of a rigid high-strength structure to transmit loads from the chair and patient to
the van floor structure together with a rectangular center section for engagement and locking with a mating floor structure when the chair is in the lowered position (Fig. 6). Since structural integrity is being designed into, rather than being added on to the wheelchair, the minimum Department of Transportation restraint requirements will readily be met.

Stable and smooth operating characteristics in uneven terrain will be made possible by suspension of the wheels from the center section, on leading and trailing arms. The trailing arms will incorporate the drive motors and drive train for the rear wheels, which will have pneumatic tires (Fig. 7). The leading arms will be a four-bar mechanism for maintaining the front wheel steering system in a vertical position. The leading and trailing arms will be attached to the center section by two transverse shafts—one for the two leading arms, the other for the two trailing arms. Each arm will be mounted on its respective shaft through a rubber torsion spring. An antisway torsion bar will connect the two leading arms and another may be added to the rear arms if found necessary. In this arrangement each of the suspension arms will be independent of the others, thereby providing a relatively soft ride with excellent “rack” accommodations.

Two electromechanical actuators, controlled by the patient, will control the angle of rotation of the two suspension shafts and hence the angulation of the trailing arms (i.e., the seat height) relative to the ground. With the arms horizontal, the seat will be in its lowest position. Rotating the arms downward approximately 35 deg will raise the seat
over 8 in. to its highest position. Since the front and rear arms can be controlled independently, a limited degree of seat tilt may be obtained. Two torsion springs will be used to offset the static weight of the chair and patient. Automatic leveling circuitry may be included to keep the seat and patient level while going up and down inclines.

The requirements for higher outdoor speeds and rough terrain operation make castered front wheels undesirable. Their shimmy characteristics at high speeds, and the poor directional stability of castered wheels on rough surfaces, would require the use of a complex damping system. For this reason, the MED, Inc., wheelchair will steer one or both front wheels through a closed-loop continuously variable servomechanism. The controlled wheel(s) will be steerable through 190 deg (110 deg to the inside, 80 deg to the outside) in the first pre-production versions of the chair, and through 315 deg (160 deg to the inside, 155 deg to the outside) in later versions.

Steering and speed control will be accomplished through a single joystick. The electronic control system is being designed specifically for these chair requirements and will employ integrated circuits and power transistors to achieve a simplified package with improved efficiency compared to systems commercially available at present. Pulse-width-modulated servoamplifiers, with position feedback from the steering mechanism and velocity feedback from the drive wheels, will be used. The battery, electronics package, motors, and reduction drive trains will be optimized so as to obtain a maximum cruise radius per battery charge, maintain a top speed capability on level ground of 10 m/h, and possess the ability to climb a 20 percent grade. A stepped or continuously variable transmission may be incorporated into the trailing arm drive assemblies in order to obtain increased performance.

Good stability at all heights will be achieved by incorporating acceleration, speed, and inclination-limiting circuitry into the chair control system. The control limiting action will increase as the seat height increases (in the lowered position, the low center of gravity of the chair and its occupant will ensure stability with little or no limiting). When backing up, reverse-speed limiting circuits will prevent unsafe speeds. The power steering ratio will automatically vary as a function of speed and seat height, thereby preventing too tight a turn at high speeds or with a potentially unstable height. Additional provision for adjusting the limiting circuits to meet the weight of the patient and his physical and psychological condition may be provided. Limiting circuitry will be realized by analog circuits in early prototypes, and may be achieved with software and a microcomputer in later models. If a microcomputer is used, it will also be programmed to perform a combination (ignition) lock function. When the wheelchair is mated to the van, the same microcomputer may be used for failure detection and system reconfiguration functions.
A seating arrangement which will meet safety, postural stability, and patient comfort requirements is being designed. A series of clinical trials with an adjustable seat is planned to establish a range of seat dimensions preferred by various groups of patients and fitting 90 percent of the adult population. Shoulder restraints and a lap safetybelt will be included. The headrest will be an integral part of the molded-fiberglass contoured seat of the wheelchair.

The van-compatible wheelchair will be complex. However, much of the complexity in terms of the number of functions performed will be realized by highly reliable electronic circuitry. The mechanical design itself will be straightforward, and is expected to be both durable and trouble-free. Wherever possible, modular construction will be utilized, especially in the electronic circuitry.

Test sets which will allow semiskilled personnel to service the vehicle are planned as part of the development.

Despite its degree of sophistication, operation of the wheelchair will be made easy for either patients or attendants. All controls will require less than 8 oz. of activation force. A single joystick will provide speed control, braking, and steering control. Pushbutton or bat-handle switches will activate the height controls, parking brakes, lights, turn indicators, and warning bell. Additional equipment such as a CB radio to summon aid, combination lock, etc., will be similarly controlled. The use of a chin controller instead of a finger-activated joystick, and voice-actuated controls instead of manual switches, are also being considered. For all designs, accepted human factors engineering principles will be employed. Many functions, such as speed-limiting, and battery recharging from the van electrical system, will be automatically performed. An instrument panel may be included which will indicate the status of the wheelchair (e.g., battery charge low, speed being limited, motors overheating, etc.) Provisions are planned to allow recharging the battery from any 120V a.c. 60 Hz source, or from the van electrical system.

An attendant's control panel on the rear of the chair will be included.

The van-compatible wheelchair will meet nearly all of the design criteria as listed in section 3, part B (Design Criteria). However, considering the current state of technology, it is felt that meeting all of the design criteria would not as yet be cost-effective, so some compromises must be made. Since conveying the patient over small to intermediate distances is felt to be the primary objective, some compromise in indoor maneuverability seems justified. Therefore, the first models of the van-compatible wheelchair will have indoor maneuverability comparable to that of conventional wheelchairs, which is somewhat lower than criteria 21(a), 21(b), and 21(c) of section 3. (Table 1 indicates the relative maneuverability for an E & J Premier wheelchair, the University of California powered reclinable, adjustable-height and narrowing (PRAHN) wheelchair, and the MED, Inc., van-compatible wheelchair.) The MED
wheelchair will not have the indoor maneuverability of the UC/PRAHN chair, but will generally have superior outdoor performance and be van-compatible.

The MED van-compatible wheelchair will be considerably heavier than a conventional wheelchair, as weight will be accepted in return for performance whenever necessary. As a result, the chair will not be as easily pushed by an attendant in the event of a malfunction. However, breakdowns are expected to be very rare.

Finally, no provisions for full leg and back extension (criterion 30) or curb climbing (criterion 31) are planned at this time.

B Progress as of September 30, 1976

A mockup of the current design of the van-compatible wheelchair was constructed (Fig. 8). The mockup was made primarily to test the control characteristics of the wheelchair and evaluate the economic and production feasibility of the current design.

Generally, the results were encouraging. The chair proved to be stable at all speeds and was easy to steer. Originally, it was planned to point both front wheels in the same direction and allow any steering errors to simply reduce the tendency to move—unfortunately, in sharp turns the steering errors tended to stop the wheelchair. Two possible solutions to this problem were apparent; properly orient the front wheels so that steering errors are eliminated, or caster one front wheel and steer the other. Since proper orientation of both front wheels would require monitoring wheelbase changes as the height of the chair was varied, the first solution does not appear to be accomplishable through simple mechanical linkages. Electronic calculation of the proper alignment and orientation of the front wheels is possible, but would require an extra steering motor, servo amplifier, and calculating circuits. To try to retain simplicity in design, therefore, one front wheel of the mockup was castered and the other front wheel left connected to the steering motor. The results were much better than anticipated. There was no tendency for the wheelchair to steer in an undesired direction, and the castered wheel quickly damped after hitting bumps, etc. Steering only one front wheel may be adequate for final designs.

The mockup also failed to meet the hill-climbing criteria as the servo amplifiers did not deliver sufficient current to the drive motors. In order to achieve the desired performance, this circuitry is being redesigned.
<table>
<thead>
<tr>
<th></th>
<th>E&amp;J Premier 16-inch adult wheelchair</th>
<th>UC/PRAHN wheelchair</th>
<th>Mobility van-compatible wheelchair</th>
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<tr>
<td></td>
<td>Seat height</td>
<td>Normal seat height</td>
<td>Maximum seat height</td>
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<td>Vertical clearance</td>
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<td>49.5</td>
<td>60</td>
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</tbody>
</table>

a Comparison of indoor maneuverability of the E&J Premier (conventional) wheelchair; the University of California powered, reclineable, adjustable-height, and narrowing (UC PRAHN) wheelchair; and the Mobility Engineering and Development, Inc., van-compatible wheelchair.

b Estimated by calculating:
  turning radius = (width - 2) + \[ (width - 2)^2 + (length - rear wheel radius)^2 \]  \[ \]
All mechanical components for the first pre-production models of the van-compatible wheelchair have been constructed. The units will be similar in appearance to the mockup model shown in Figures 6 through 8. Design of the electronics package for these models is about 80 percent complete at the time of this writing.

5. COMPREHENSIVE PROGRESS REPORT: HIGH RELIABILITY CHAIR-VAN SYSTEMS FOR HIGH LEVEL QUADRIPLEGIC PATIENTS

JULY 1, 1975 THROUGH SEPTEMBER 30, 1976

In July 1975, Mobility Engineering and Development, Inc., was to have begun the development of a wheelchair and van system in which the van is operated in conjunction with the patient's personal wheelchair controls. Due to severe budget reductions, this development was de-
layed until April 1976, when it was started on a limited scale. The research and development effort will be greatly expanded beginning in October 1976.

A. Basic Description

Figure 9 shows a block diagram of a chair-van system in which the van may be operated using the patient's personal wheelchair controls. For operation the patient would drive the wheelchair into the van using an elevator lift installed in the rear or side of the van, and position himself approximately where the driver's seat is located in a conventional van. A special guide rail system built into the van would facilitate mating the wheelchair to the van.

Once they are mated, several events would occur. The wheelchair would be further secured to the van to meet Department of Transportation standards, and the wheelchair battery would become part of the van electrical system, with the van either recharging the wheelchair battery or using it as a source of emergency energy. A control panel mounted on the wheelchair would become active for control of such van functions as starting and turning off the ignition, lights, turn-signals, shifting gears, radio operation, etc. Whenever the van ignition was turned on, the wheelchair joystick control would then be automatically switched from control of the wheelchair to control of the van (another control panel permanently mounted in the van would be used for display and control of less frequently used accessories such as the heater, air conditioner, windshield wipers, etc.).

Operation of the joystick for control of the van would differ only slightly from operation for control of the wheelchair alone. Both the reverse speed limiter and the automatic steering ratio compensator (ASRC) of the wheelchair control system would be retained in a modified form for control of the van. The speed of the van would be limited to about 10 m/h in reverse, and the ASRC would permit maximum steering at 0 m/h (about ±40 deg from the line of progression), but only about ±10 deg turning capability from straight ahead at 55 m/h. The steering ratio would thus be a function of the vehicle's speed and not of the joystick position or the engine rpm.

The control system for the van must be highly reliable, with redundancy for safety in the event of a malfunction. Such high reliability systems may be designed in several ways. For example, a system which functions at a normal reliability level can be redesigned so that every component in the system is "overdesigned" and a lower probability of failure results. Unfortunately, such systems can still fail, and often the operator gets no warning of an impending failure. Another approach is to use redundancy: in such systems every key component is duplicated, and either component alone is sufficient to keep the system operating.
Figure 9. — Block diagram for van control system.
Provisions for warning the operator that a failure has occurred may or may not be included. (A reasonable visual inspection schedule will usually locate failures before two identical failures can occur, and two identical failures must occur before there is a potentially dangerous failure.)

In addition, more exotic high-reliability systems are possible (e.g.; triple redundant “failsafe” systems, computer failure detection, etc.). MED, Inc., has analyzed several high-reliability systems for implementation in its chair-van system. After selection of a design, it should be possible to proceed to eliminate those backup systems for components with a low probability of failing and low potential for injury upon failure —the more obvious ones should be able to be eliminated during the design phase or by simulation of the system in the laboratory, the less obvious ones by road tests of an actual model. At present, a design has been conceptualized which we believe will greatly exceed most of our reliability requirements. The conceptualized system would use secondary and tertiary backup systems with a microcomputer failure-detector, and a “failsafe” mode. In essence, every major component in the control system would be triplicated, thus creating three subsystems. Two of these subsystems would be capable of controlling the van while the third would be used as a high-reliability comparison system. Approximately 100 to 1000 times per second, the microcomputer would sample and compare all critical points in the three subsystems. Normally, all three subsystems would be identical within a prespecified tolerance. However, if a failure occurred, two of the subsystems would be the same while the third would deviate. A majority, or two-of-three, voting scheme would then usually be applied in which case van control would be transferred to a majority subsystem. At the same time, a malfunction indication would be displayed for the driver, probably by both a panel lamp and an endless-loop tape annunciator which would repeat a short message about once per minute. The van could still be driven until repair of the malfunction was possible.

In the unlikely event that two separate malfunctions occurred in separate subsystems simultaneously, the three subsystem outputs would all be different. The microcomputer would then attempt to connect functioning blocks of separate subsystems so as to form one functioning system. If this were not possible, then a failsafe mode of operation would result in which the front wheels would be aimed straight ahead and a moderate brake applied. The driver would be warned not to drive the vehicle until repairs could be made.

In addition, the three subsystems would be compared at all times by the microcomputer to a table of expected system parameters. If any of the subsystems deviated from the table, a malfunction signal would be displayed and the probable cause indicated. If two identical subsystem
failures occurred simultaneously, the microcomputer would detect the condition, and then choose the one functioning subsystem to control the van (if it were not the comparison system). If it were the comparison system, the microcomputer would place the system in a failsafe mode.

Computer operation would also be continually checked, and if a computer failure occurred that was critical, control would be transferred to a simpler majority-voting-scheme controller implemented by hard wired logic or a second microprocessor. In the very unlikely event that two failures occurred in separate subsystems simultaneously, and at the same time the microcomputer failed, provisions for manually entering the failsafe state could be selected by the driver.

Additional features which may be incorporated into the system include: limited-range (less than 15 ft) telemetry control of the van from the wheelchair, to be used in the event that the elevator lift became blocked by another vehicle; a CB radio with automatic emergency capabilities in the event of an accident; and provisions for operation by non-handicapped individuals.

B. Progress As of September 30, 1976

Progress to date has primarily been in terms of conceptualization of the system on paper. Limited work has begun on a bench mockup of a multiple redundancy chair-van control system with failsafe, computer failure-detection, and computer system-reconfiguration modes of operation. The mockup will be used to determine the feasibility of several different chair-van control configurations.

C. Planned Development: Three Systems

To develop a high reliability chair-van control system, it is planned to construct and test a bench mockup and incorporate the results of the mockup testing into three chair-van prototype systems. They are as follows:

System 1—Chair-van controlled by two joysticks (one for the wheelchair, the other for the van) in conjunction with finger or mouthstick operated pushbutton switches (starting January 1977).

System 2—Chair-van controlled by a single wheelchair joystick, (chin or shoulder control) in conjunction with finger or mouthstick operated pushbutton switches (starting September 1978).

System 3 — Chair-van controlled by a single wheelchair joystick (shoulder or chin control) in conjunction with a voice-recognition system (starting September 1978).

Note that a simple majority voting scheme would transfer control to one of the two malfunctioning subsystems in this case.
The first system would be a developmental prototype system to aid in testing the design and system function. System 1 would not allow the van to be driven from a wheelchair-mounted control panel. Instead, all necessary van controls including a separate van joystick would be mounted permanently in the van, in a position easily accessible to the driver. Such an approach would avoid potentially troublesome mating connector reliability problems, would reduce the difficulty of achieving transfer of control between the wheelchair and the van, and would facilitate troubleshooting the first two vans when the wheelchair was not available.

Mating connections for recharging the wheelchair battery from the van electrical system would probably be attempted in System 1.

System 2 would allow driving the van with controls that are permanently attached to the wheelchair. Mating connector reliability should be achieved by using only four connections between the wheelchair and the van: two for connecting the wheelchair battery to the van electrical system, and two more for bidirectional transfer of time-multiplexed control data. An encoder on the wheelchair could time-multiplex all control signals originating from the wheelchair, while a decoder in the van could route the signals to their proper destinations. In the reverse direction, an encoder in the van could transfer data to a decoder mounted on the wheelchair. Other approaches will be studied, including the use of telemetry, or of a high-reliability 100-pin connector.

Several types of controls for patients with different levels of disability (i.e., remaining function) are envisioned. For patients with residual hand and arm function (on at least one side) a joystick and a push-switch control box may be used. Patients with more severe involvement may be provided with chin or shoulder controls for steering, brakes, and speed control. A push-switch or bat handle toggle switch control box, operated by an offset or collapsing mouthstick, might be useful for some patients; breath control switches might be utilized by others.

The third system would replace the pushbutton-switch control box of System 2 with a voice (utterance) recognition system. The voice recognition system would be used only for control of auxiliary on-off functions. Control of steering, brakes, and throttle would still be accompl-
Table 2.—Sample vocabulary for the voice recognition system.

<table>
<thead>
<tr>
<th>Command</th>
<th>Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. TURN</td>
<td>enables turn indicator circuits for a LEFT or RIGHT command</td>
</tr>
<tr>
<td>2. WIPER</td>
<td>enables windshield wiper circuits for an ON or OFF command</td>
</tr>
<tr>
<td>3. WASHER</td>
<td>enables windshield washer circuits for an ON or OFF command</td>
</tr>
<tr>
<td>4. FLASH</td>
<td>enables emergency flasher circuits for an ON or OFF command</td>
</tr>
<tr>
<td>5. PUMP</td>
<td>enables emergency hydraulic pump for an ON or OFF command</td>
</tr>
<tr>
<td>6. BRAKES</td>
<td>enables emergency parking brake circuits for an ON or OFF command</td>
</tr>
<tr>
<td>7. HORN</td>
<td>immediately sounds two one-half second honks of the horn in rapid succession</td>
</tr>
<tr>
<td>8. IGNITION</td>
<td>readies the van ignition circuits for an ON, OFF, or START command</td>
</tr>
<tr>
<td>9. SHIFT</td>
<td>readies the gear shifting circuits for a PARK, REVERSE, NEUTRAL, DRIVE, SECOND, or FIRST command</td>
</tr>
<tr>
<td>10. INTERIOR</td>
<td>readies the interior light circuits for an ON or OFF command</td>
</tr>
<tr>
<td>11. PARKING</td>
<td>readies the parking light circuits for an ON or OFF command</td>
</tr>
<tr>
<td>12. HEADLIGHTS</td>
<td>readies the headlight circuits for an OFF, LOW, or HIGH command</td>
</tr>
<tr>
<td>13. DOORS</td>
<td>readies the lift door circuits for an OPEN or CLOSE command</td>
</tr>
<tr>
<td>14. LIFT</td>
<td>readies the lift circuits for an OPEN, CLOSE, RAISE, or LOWER COMMAND</td>
</tr>
<tr>
<td>15. SEAT</td>
<td>readies the seat restraint circuits for a LOCK or RELEASE command</td>
</tr>
<tr>
<td>16. WINDOW</td>
<td>readies the driver's window circuits for an OPEN or CLOSE command</td>
</tr>
<tr>
<td>17. LEFT</td>
<td>modify the TURN command</td>
</tr>
<tr>
<td>18. RIGHT</td>
<td>modify the TURN command</td>
</tr>
<tr>
<td>19. ON</td>
<td>modify the WIPER, WASHER, FLASH, PUMP, BRAKES, IGNITION, INTERIOR, PARKING, and HEADLIGHTS</td>
</tr>
<tr>
<td>20. OFF</td>
<td>(ON not recognized) commands</td>
</tr>
<tr>
<td>21. START</td>
<td>modifies the IGNITION command</td>
</tr>
<tr>
<td>22. PARK</td>
<td>modify the SHIFT command</td>
</tr>
<tr>
<td>23. REVERSE</td>
<td>modify the SHIFT command</td>
</tr>
<tr>
<td>24. NEUTRAL</td>
<td>modify the SHIFT command</td>
</tr>
<tr>
<td>25. DRIVE</td>
<td>modify the SHIFT command</td>
</tr>
<tr>
<td>26. SECOND</td>
<td>modify the SHIFT command</td>
</tr>
<tr>
<td>27. FIRST</td>
<td>modify the SHIFT command</td>
</tr>
<tr>
<td>28. HIGH</td>
<td>modify the HEADLIGHTS command</td>
</tr>
<tr>
<td>29. LOW</td>
<td>modify the HEADLIGHTS command</td>
</tr>
<tr>
<td>30. OPEN</td>
<td>modify the DOORS, LIFT, and WINDOW commands</td>
</tr>
<tr>
<td>31. CLOSE</td>
<td>modify the DOORS, LIFT, and WINDOW commands</td>
</tr>
<tr>
<td>32. RAISE</td>
<td>modify the LIFT command</td>
</tr>
<tr>
<td>33. LOWER</td>
<td>modify the LIFT command</td>
</tr>
<tr>
<td>34. LOCK</td>
<td>modify the LIFT command</td>
</tr>
<tr>
<td>35. RELEASE</td>
<td>modify the LIFT command</td>
</tr>
</tbody>
</table>

a Commands 1-6 or 8-16 would be uttered first, followed by commands 17-35 (e.g., “SHIFT-DRIVE” would place the transmission into drive gear).
lished by means of a chin or shoulder controller.¹ It is felt that many
quadriplegics with complete lesions at the C-5 level should be able to
drive using this system.

The voice recognition system would be required to recognize about 35
different utterances. Table 2 indicates a sample of the vocabulary that
might be used. All commands would require two utterances except
“HORN,” which would immediately cause two half-second honks in
rapid succession.

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MED, Inc., believes that, considering the present state of technology, driving functions
such as steering, braking, and speed control still require a high quality analog signal if
they are to be safely implemented. Control systems utilizing voice commands such as
“TURN-LEFT” appear unsafe, whereas brakes (e.g., “BRAKE-SOFT”) and throttle
(e.g., “GO-FORTY”) voice commands seem at best only marginal.

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