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Boeing Aerospace Co, Seattle, WA

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Morgantown People Mover
Inductive Communications System Design Summary

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December 1978

Final Report

U.S. DEPARTMENT OF TRANSPORTATION
Urban Mass Transportation Administration
Office of Technology Development and Deployment
Washington, D.C. 20590

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16. Abstract

This report documents the experience obtained during the design and development of the Inductive Communications System used in the Morgantown People Mover. The Inductive Communications System is used to provide wayside-to-vehicle and vehicle-to-wayside communications for command and control signaling. To aid future designers, system design and supporting analyses are discussed.

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PREFACE

This report documents the experience obtained during the design and development of the Inductive Communication System (ICS) used on the Morgantown People Mover (MPM). The ICS system design evolution, problems encountered and the rationale for their solution, supporting analytical modeling, and recommendations are presented so that future system designers can benefit from our experience.

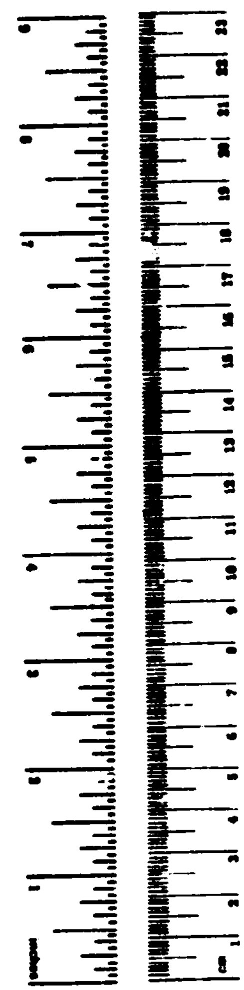
Work described in this report was done for the U.S. Department of Transportation, Urban Mass Transportation Administration. The ICS development and production was accomplished under contract to The Boeing Company, Seattle, Washington, as prime contractor and The Bendix Corporation, Ann Arbor, Michigan, as principal subcontractor. Some of the early studies and early design decisions were made by the Jet Propulsion Laboratory (JPL), Pasadena, California. This report was contracted for by the Transporation Systems Center (TSC), Cambridge, Massachusetts.

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

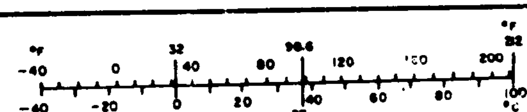
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in ≡ 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



CONTENTS

ILLUSTRATIONS

Figure		Page

TABLES

GLOSSARY

AGC	automatic gain control
APL	Applied Physics Laboratory
AWG	American wire gage
CAS	collision avoidance system
CCCS	central control and communications system
C&CS	control and communictions system
CW	continuous wave
DHU	data handling unit
DSU	destination selection unit
ECU	environmental control unit
EMC	electromagnetic compatibility
EMI	electromagnetic interference
FCC	Federal Communications Commision
FSK	frequency shift keying
I&CO	integration and checkout
ICS	inductive communications system
JPL	Jet Propulsion Laboratory
MPM	Morgantown People Mover
NRZ	nonreturn to zero
PLL	phase lock loop
SCCS	station control and communications subsystem
SCR	silicon controlled rectifier
SIL	system integration laboratory
STTF	Seattle Transportation Test Facility

UMTA	Urban Mass Transportation Administration
UPS	uninterruptible power supply
VCCS	vehicle control and communications system
WVU	West Virginia Univesity

1. INTRODUCTION

1.1 GENERAL

This report summarizes the design and development work on the wayside-to-vehicle inductive communications link for the Morgantown People Mover (MPM) system. Since the MPM was developed in three phases, the third phase currently being installed, this report presents a coherent analysis of design versus experience that occurred over a 7-year span and concludes with some observations important for future usage of this type of system. This development is presented in the following sections:

Section 1. Introduction (general and historical)
Section 2. General system description
Section 3. Inductive communications design evolution
Section 4. Communications link analysis
Section 5. Recommendations

The scope of the Inductive Communication System (ICS) is that set of wayside and vehicle electronics for uplink (wayside-to-vehicle) and downlink (vehicle-to-wayside) signaling that implements collision avoidance, vehicle longitudinal control, vehicle door control, and status reporting throughout this report. The system that operated through June 1978 (phase IB) will be used as the system baseline, and the Morgantown expanded system (phase II), under contract at the time this report was written, will be presented as changes from this baseline. In section 3. an emphasis is placed on the major hardware design problems encountered and their resolution. The interaction of system operating parameters are discussed along with recommendations for improvements to the inductive communications concept as implemented.

1.2 HISTORY

The Morgantown project, which began in 1969, is an Urban Mass Transportation Administration (UMTA) demonstration program that provides a personal rapid transit system (fig. 1-1) between the central business district of Morgantown, West Virginia, and the widely separated campuses of West Virginia University (WVU). The MPM system is an automated, two-mode (schedule and demand) transit

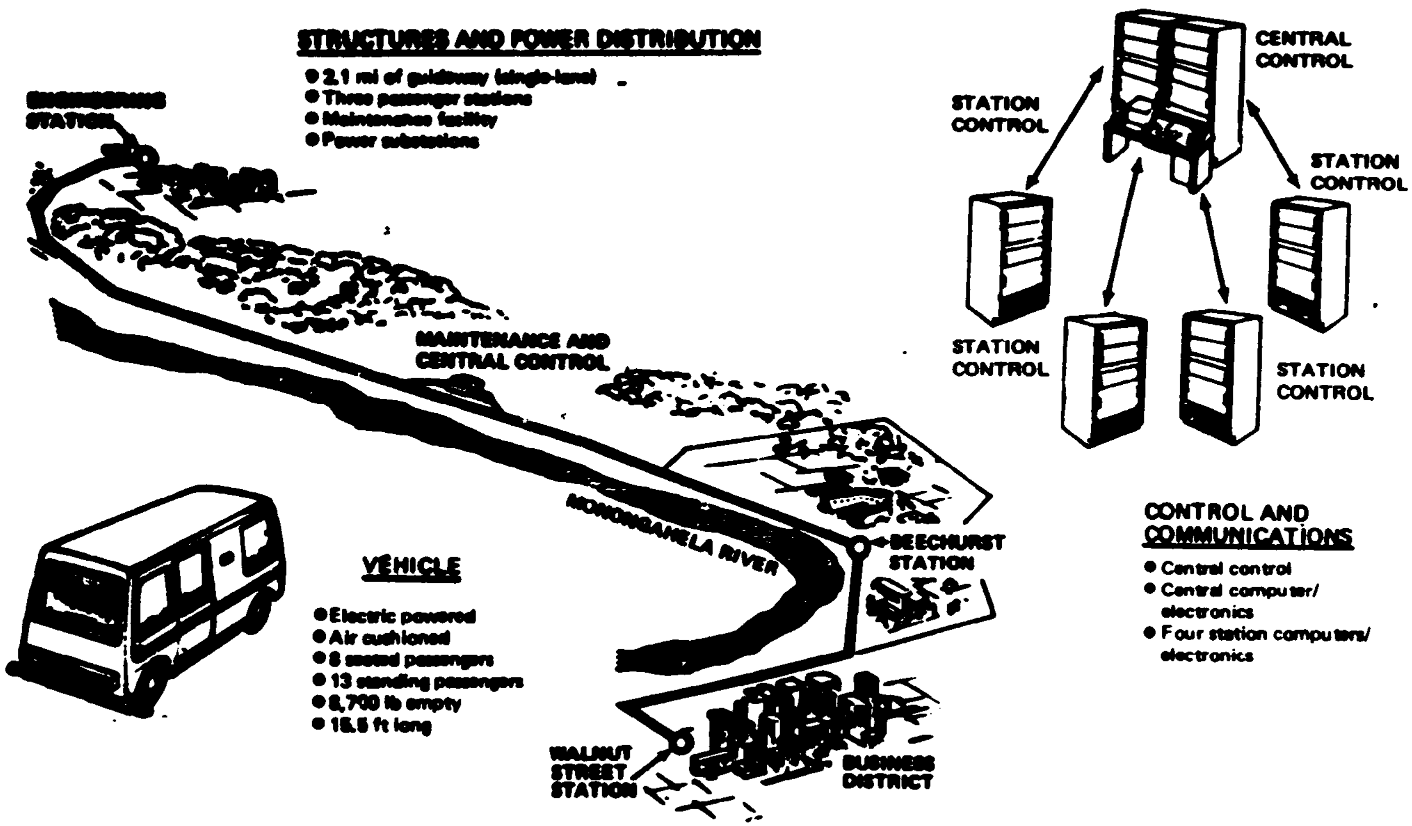


Figure 1-1. MPM System Elements (Phases IA and IB)

system that consists of a fleet of electrically powered, rubber-tired, passenger-carrying vehicles, operating on a dedicated guideway network under computer control.

The project began with a research grant given to WVU in 1969. Initially, it was to be an expanded version of a system already developed by the Alden Company of Natick, Massachusetts. However, in mid-1970 it was determined that a new system would be created under requirements and constraints established jointly between WVU and UMTA. The Jet Propulsion Laboratory (JPL) was selected as system manager and designer in 1970; they did the preliminary analyses and trade study. Contracts were let to Boeing for vehicle design and fabrication in May 1971 and to Bendix Company for communications and control of a six-station system. In September 1971, with much of the system design completed, UMTA transferred system management responsibility from JPL to The Boeing Company. Also at this time, the program was phased to first build a three-station system (phase I) and later expand to a six-station system (fig. 1-2) in phase II.

Phase I was divided into a phase IA and a phase IB. Phase IA, completed in September 1973, resulted in a prototype system comprising 5.2 miles of single-lane guideway, three passenger stations, a maintenance and central control facility, and five test vehicles. Phase IB provided the additional facilities required for public service including a fleet of 45 vehicles. Phase IB also provided the opportunity to resolve the problems encountered in the prototype phase IA system. Phase IB testing concluded with the system being opened to passenger service in September 1975. The system is of modular design, allowing growth from the present configuration to an expanded configuration which will accommodate 73 vehicles and two new stations for the phase II expansion. In November 1976 approval of the phase II MPM program was granted. Design and construction of two new stations, 3.4 miles of single-lane guideway, and 28 new vehicles, along with certain rework and retrofit tasks is underway and will be completed by mid 1979. The inductive communications system used in the new portions of the track was redesigned to improve system availability and reduce costs. Figure 1-2 shows the present guideway configuration and the three basic system elements: the vehicle system, the structures and power distribution system, and the control and communications system (C&CS).

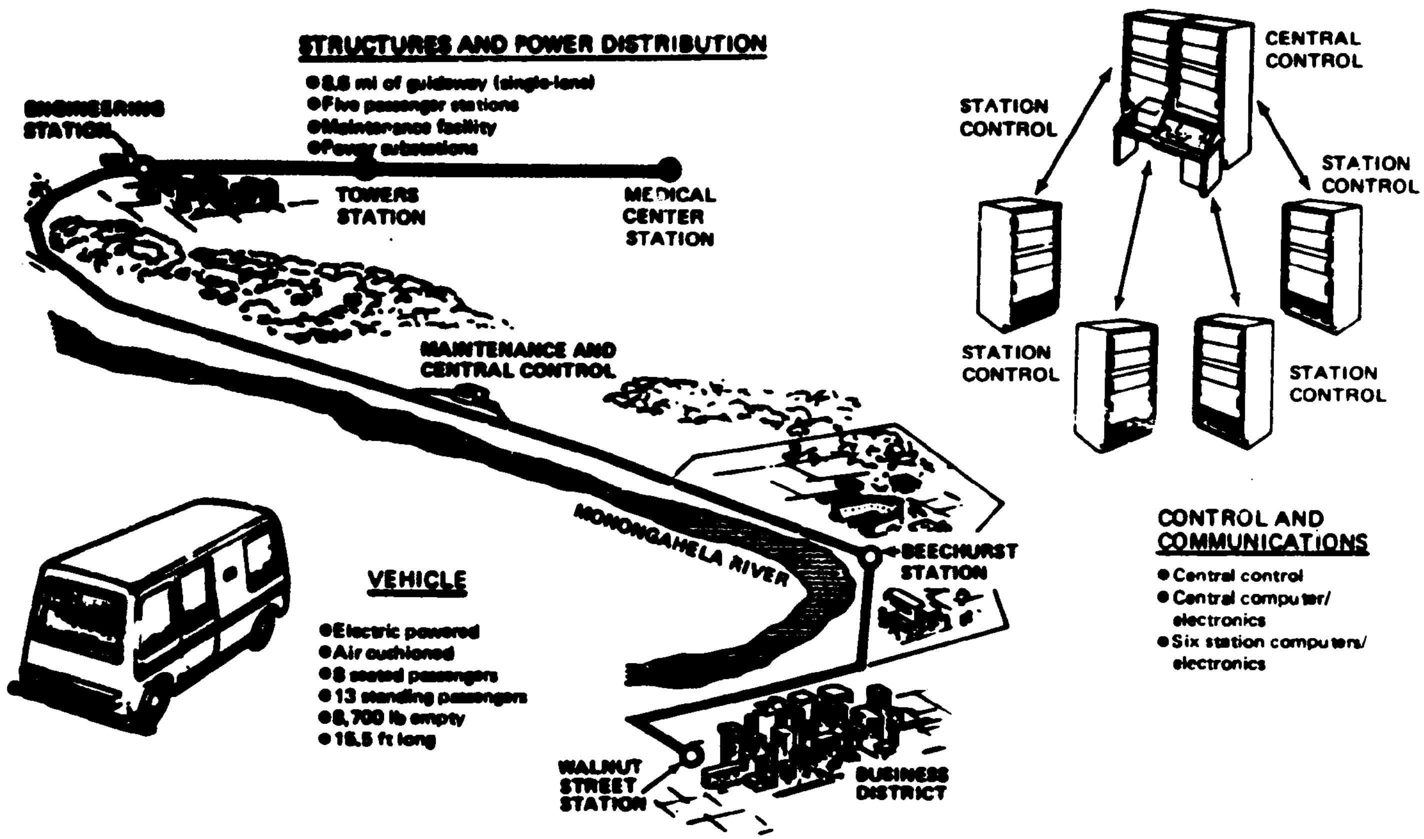


Figure 1-2. MPM System Elements (Phase II)

The inductive communications portion of the C&CS is the subject of this report. The chronology of its design history or evolution is depicted in figure 1-3. The various changes to the inductive communications system as they relate to these phase-oriented events are discussed in section 3.

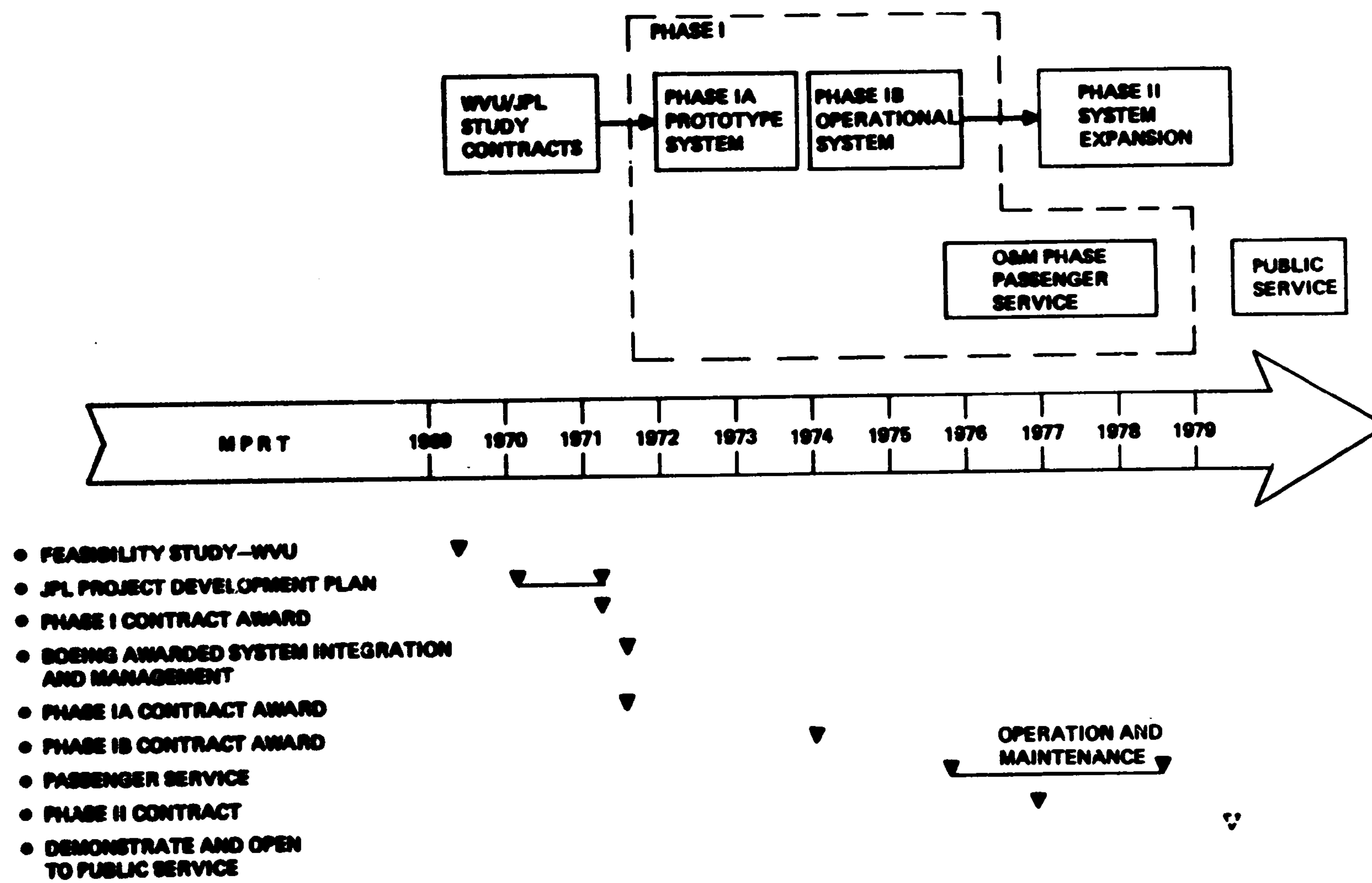


Figure 1-3. Program Evolution

2. GENERAL SYSTEM DESCRIPTION

The present operational (phase IB) Morgantown People Mover (MPM) system consists of the Walnut, Beechurst, and Engineering stations, a vehicle maintenance facility with a small test loop, a central control facility, and 45 electrically powered, rubber-tired vehicles. The three stations and maintenance facility are interconnected by a dual-direction guideway network. Vehicles are dispatched and monitored by the Control and Communications System (C&CS) computers located in the central control facility and each station. A safe headway is independently ensured by the Collision Avoidance System (CAS), which monitors vehicle location by inputs from presence detectors located along the guideway. Should a vehicle approach too closely to the vehicle in front of it, the CAS will cause the vehicle to initiate emergency braking and stop. The CAS also provides protection at merges to avoid simultaneous arrivals. Vehicle speed is maintained by the onboard Vehicle Control and Communication System (VCCS) to conform to the assigned guideway civil speed that is continuously communicated to the vehicle through the C&CS. The main guideway is divided into four segments, each under control of the nearest station (for control purposes the maintenance facility is considered a station).

2.1 STATION CONTROL AND COMMUNICATIONS SUBSYSTEM

Under system control from the Central Control and Communications System (CCCS), the Station Control and Communication Subsystem (SCCS) performs the control and monitoring functions for local transit operations at the three passenger stations and the maintenance facility. The station computer commands vehicle operations; i.e., switching, stopping, and door operation. The station computer also commands the station dynamic displays and responds to inputs from the passenger-activated Destination Selection Units (DSU).

Equipment installed on the guideway that are required to control and monitor vehicle progress include Frequency Shift Keying (FSK) and signal tone loops, switch and high-speed enable magnets, vehicle presence detectors, and the cabling required to electrically connect these elements to the station. All active electronics that drive the signal cables are located in the station and maintenance facility C&CS equipment rooms and are powered by an uninterruptible power supply (UPS). Station-generated commands are inductively coupled to the vehicle from control loops buried in the guideway just under the running surface.

The inductive communications data link transmits vital signals by tones and nonvital signals by FSK digital data message transmissions to vehicles on the guideway. Inductive communications are accomplished using (1) guideway-embedded loop antennas, which are connected to associated transmitting and receiving units in the station equipment room, and (2) vehicleborne receiving and transmitting antennas that in turn couple signals to the vehicleborne VCCS electronics.

Loop antennas are embedded throughout the entire guideway. Each loop antenna consists of two parallel lengths of wire physically separated by 6 in and installed in slots. Each loop is resistively loaded to match the impedance of its driver. The loops are connected to a transmitter or receiver in the station with twisted, shielded wire pairs. Loop lengths and locations vary depending on their function. Each loop is balanced to every other loop using crossovers in appropriate loops, to prevent crosscoupling of signals between two or more loops occupying the same guideway slot. All transmitting loops (uplink) are located to the right of the guideway centerline in the direction of vehicle travel. Receiving loops (downlink) are located to the left of the vehicle centerline.

2.2 INDUCTIVE COMMUNICATIONS SUBSYSTEM

Station-to-vehicle inductive communication via the guideway loops is illustrated in figure 2-1. The transmissions consist of FSK data messages (uplink and downlink), speed tones, switch tones, switch verification downlink tones, station stop tones, calibration tones, and safe tones (part of CAS). FSK data messages and speed tones are transmitted uplink via common loops that are embedded throughout the entire guideway. The length and location of individual FSK/speed tone loops are primarily functions of the distance from a station and the guideway speed zone. FSK receive loops (downlink) are located on the opposite side of the guideway. All other tone signals are transmitted via loops specifically dedicated to a single function, though coexisting in the same guideway slots as the FSK/speed tone loops. The length and location of switch tone transmitting loops are dictated

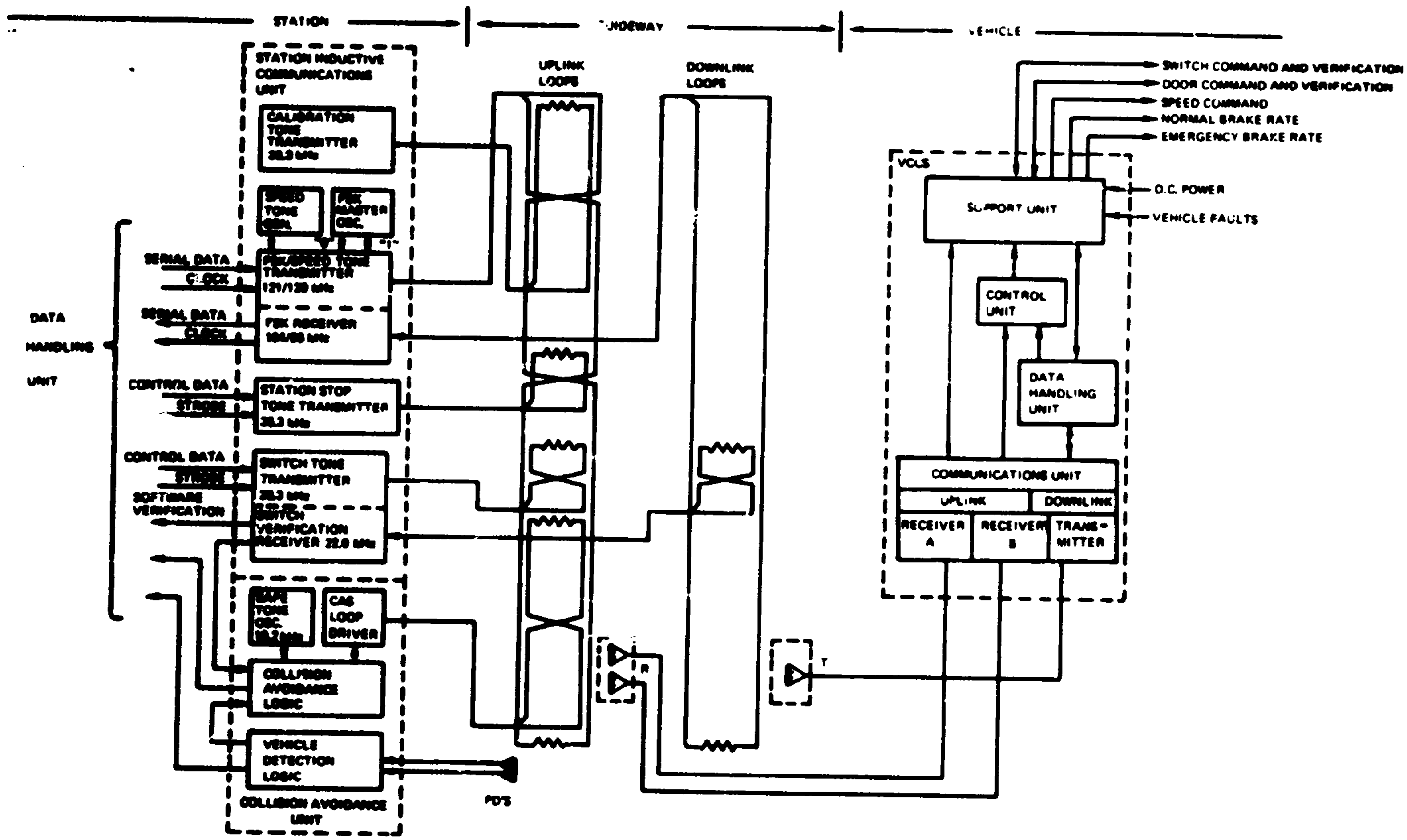


Figure 2-1. Inductive Communications Subsystem (Phase IB)

by merge/demerge patterns along the main guideway and within the station area. A switch verification receive tone loop of the same length as the transmit loop lies parallel to each switch loop and on the opposite side of the guideway in the same guideway slots as the FSK receive loop. Station stop tone loops are 12 ft long and are located at each station berthing position. Calibration tone loops are 200 ft long and are located at fixed 800-ft intervals along the main guideway. Safe tone transmitting loops are embedded along the entire guideway. These loops vary in length from 3 ft to over 200 ft, are located between vehicle presence sensors, and are sited to provide safe headway.

Vehicle-to-station communication, via guideway receiving loops, consist of FSK data message transmissions and switch verification tone signals. FSK receiving loops are embedded throughout the guideway opposite each FSK/speed tone transmitting loop.

Characteristics of the uplink and downlink transmissions between the vehicle and the station are shown in table 2-1. Each function is described in detail in the following paragraphs.

2.2.1 Uplink Communictions

Loop Driver. A loop driver provides the interface between each uplink transmitter (except safe tones) and its associated guideway loop. In the phase IB system a double push-pull circuit configuration provides the signal gain and current drive required for each loop. Input signals from the related transmitter unit are again adjusted at the input stage of the loop driver and the differential output signals are each applied through amplifiers to separate push-pull current amplifiers. The output of these current amplifiers provide a low-impedance, balanced-current drive to the guideway loop. Resistors are located in each loop to provide current limiting and impedance matching. Each current amplifier output stage has a crossover distortion adjustment to help shape the sinusoidal output and reduce distortion that causes harmonic generation.

FSK and Speed Tone Control. The FSK uplink transmits speed commands and FSK messages as shown in table 2-1 over one set of guideway loops while a second set of loops is used for receiving vehicle-generated downlink FSK messages.

Table 2-1. Signal Transmission Characteristics

Tone type	Tone carrier frequencies (kHz)										
	6.1	10.2	13.3	17.2	22.0	28.3	38.3	96	104	121	129
Uplink											
Speed tone (44 ft/s)	80		80								
Speed tone (33 ft/s)			80	80							
Speed tone (22 ft/s)	80			50							
Speed tone (8 ft/s)	80										
Speed tone (6 ft/s)			80								
Speed tone (4 ft/s)				50							
Switch tone (right)						50					
Switch tone (left)						70					
Station stop tone							Tone only				
Calibration tone							Tone only				
Safe tone		80									
FSK										▷	▷
Downlink											
Switch verification (right)					80						
Switch verification (left)					70						
FSK								▷	▷		

Note: Numerical entries indicate modulation (ON/OFF) frequency.

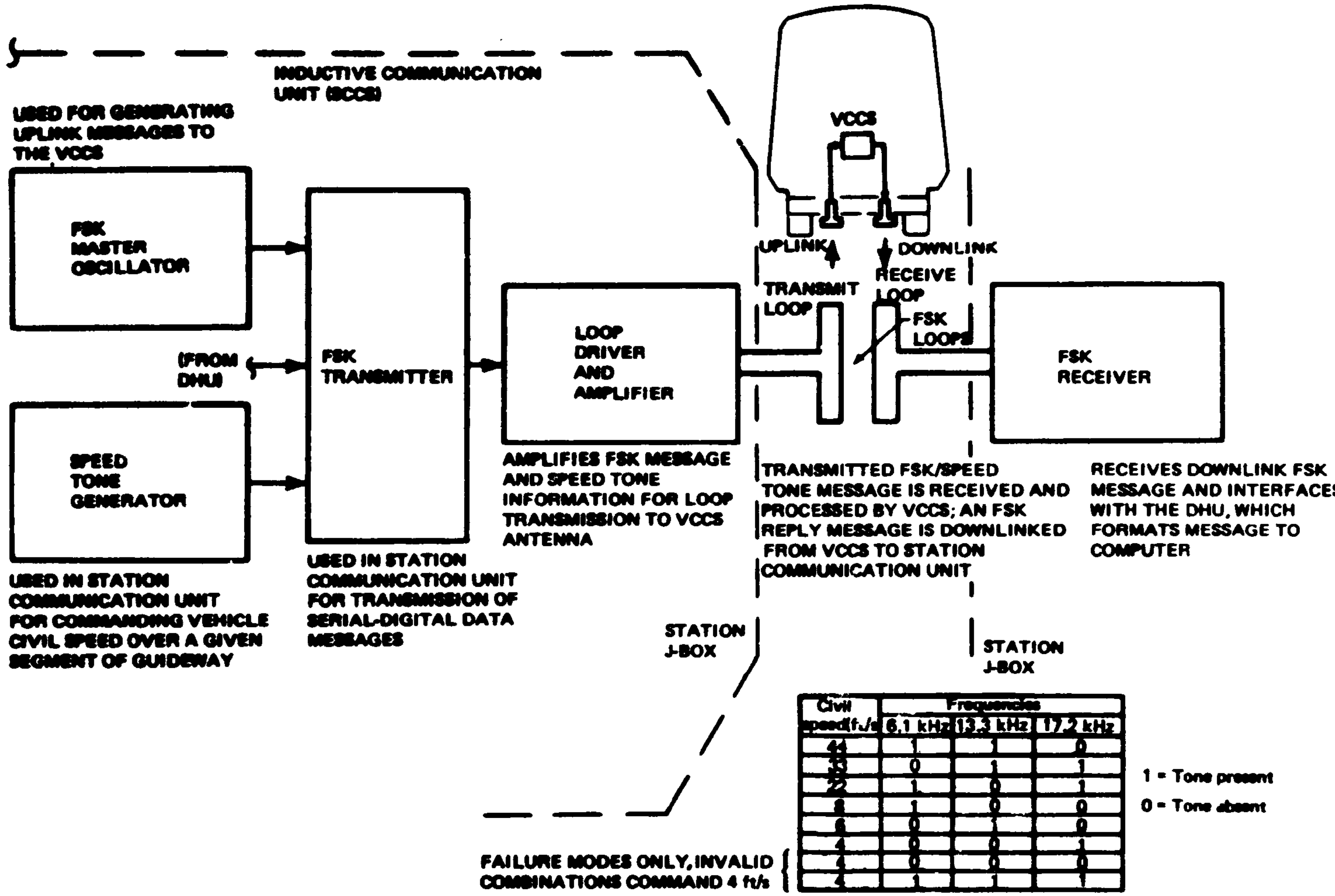
Speed tones are mixed-tone signals or individual-tone signals as indicated. When two tones are present, they are phased such that they are alternately chopped at the modulation frequency.

▷ FSK at 1-kHz bit rate, 50% duty cycle.

The phase IB FSK/speed tone units consist of a master oscillator, a speed tone generator, an FSK transmitter, and a loop driver (shown in fig. 2-2). The FSK master oscillator, which is common to several FSK transmitters, provides two continuous sinusoidal signal outputs that are amplified and level adjusted at the input to the FSK transmitter. These sinusoidal signal inputs are applied to two switching circuits that are normally gated off until serial data and gated clock inputs are applied to the transmitter control logic from the data handling unit. FSK data messages consist of a start sync bit, a 16-bit data work complement, and a stop sync bit. The data transmission rate is 1,000 bps. A logic "1" is represented by a 129-kHz tone burst during the latter half of a bit time interval. A logic "Ø" is represented by a 121-kHz tone burst during the latter half of a bit time interval. The first half of a bit time interval and the absence of any FSK data message transmission is characterized by a quiescent state.

In the phase IB system the speed-command tone signal inputs are generated in one of six possible speed tone circuit configurations that provide signal outputs corresponding to speeds of 44, 33, 22, 8, 6, and 4 ft/s. The higher command speeds utilize circuit configurations that provide signal outputs in combinations of one or two possible tones (table 2-1) alternately chopped at a 50-Hz rate. The tones are apportioned such that a single tone chopped at a 50-Hz rate defines one of the three lower speeds, and any two tones alternately chopped are required to command one of the three higher speeds. In this manner, failure of any one oscillator in the higher speed circuits will default to a lower speed command and thus remain safe. The combination of one or two tones defining a particular civil speed then is applied to the line or mixing amplifier in the FSK transmitter where it is mixed with the FSK information and level adjusted to provide the proper input signal to the loop driver, which provides the current gain required to drive the associated FSK/speed tone loop.

Vehicle Calibration. The calibration tone generator transmits a signal to the VCCS to provide a distance reference. This nonvital signal is used by the VCCS as a reference for calibrating the vehicle's odometer. Calibration tone loops are 200 ft long and generally positioned every 800 ft along the guideway. Phase IB calibration tone units comprise a calibration tone transmitter and its associated loop driver. The output from a 36.3-kHz oscillator contained in the calibration



Civil speed ft/s	Frequencies 6.1 kHz	13.3 kHz	17.2 kHz
44	1	1	0
33	0	1	1
22	1	0	1
8	1	0	0
6	0	1	0
4	0	0	1
4	0	0	0
4	1	1	1

Figure 2-2. FSK/Speed Tone Loop Control (Phase IB)

tone transmitter is fed through a bandpass filter and a buffer amplifier to the loop driver for the associated calibration loop (as shown in fig. 2-3). It should be noted that calibration loops do not contain crossovers as will be discussed later.

Station Stop Signal. When a vehicle enters a station channel, it is commanded to stop at the proper berth by the presence of a stop tone. The phase IB station stop tone units comprise a stop tone transmitter that generates a 36.3-kHz continuous tone and its associated loop driver (shown in fig. 2-4). The station stop tone transmitter is controlled by a computer-generated command data word that is decoded by the Data Handling Unit (DHU) to provide a control data and strobe signal input to the addressed station stop tone unit. A logic "Ø" in the data input commands the addressed transmitter to transmit a station stop tone when the strobe signal is applied. A logic "1" commands the addressed transmitter to remove the station stop tone. The VCCS must be receiving a 4-ft/s speed command and a stop tone for 4.5 in. of travel to begin the deceleration profile that will allow the vehicle to stop at the berth. After the vehicle has come to rest, it may be dispatched again by removing the stop tone (made possible by a door-closed verification). When the vehicle is dispatched, it will follow an acceleration profile of 2 ft/s^2 up to the assigned civil speed.

Switch Tone Control. The switch tone transmitter generates a signal to command a vehicle to "steer left" or "steer right." The vehicle is sent a switch command as it passes over the switch loop at every guideway juncture (merge or demerge). The vehicle, regardless of its previous switch position, must verify that it is in the position dictated by the switch loop command or it is brought to a stop via an interlock to the CAS. When a switch command is received that requires switching, the action and verification must take place within the time allocation shown in figure 2-5.

In the phase IB system there are three basic types of switch tone transmitters. Switch tone units used to control vehicles entering guideway demerge zones consist of a computer-controlled transmitter, a loop driver, and the associated loop. Switch tone units used to control vehicles entering guideway merge zones employ a fixed "steer right" or "steer left" switch tone transmitter, a loop driver, and

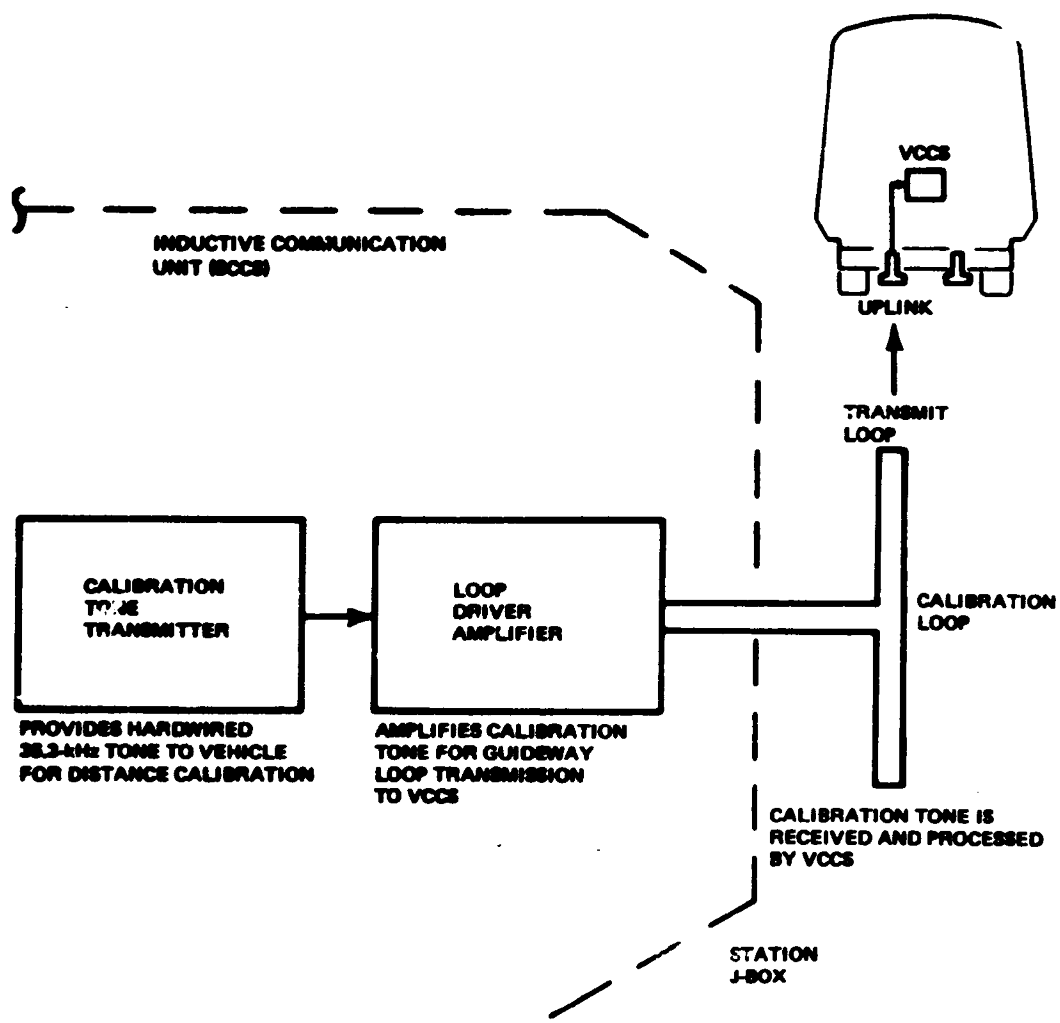


Figure 2-3. Calibration Loop Control (Phase IB)

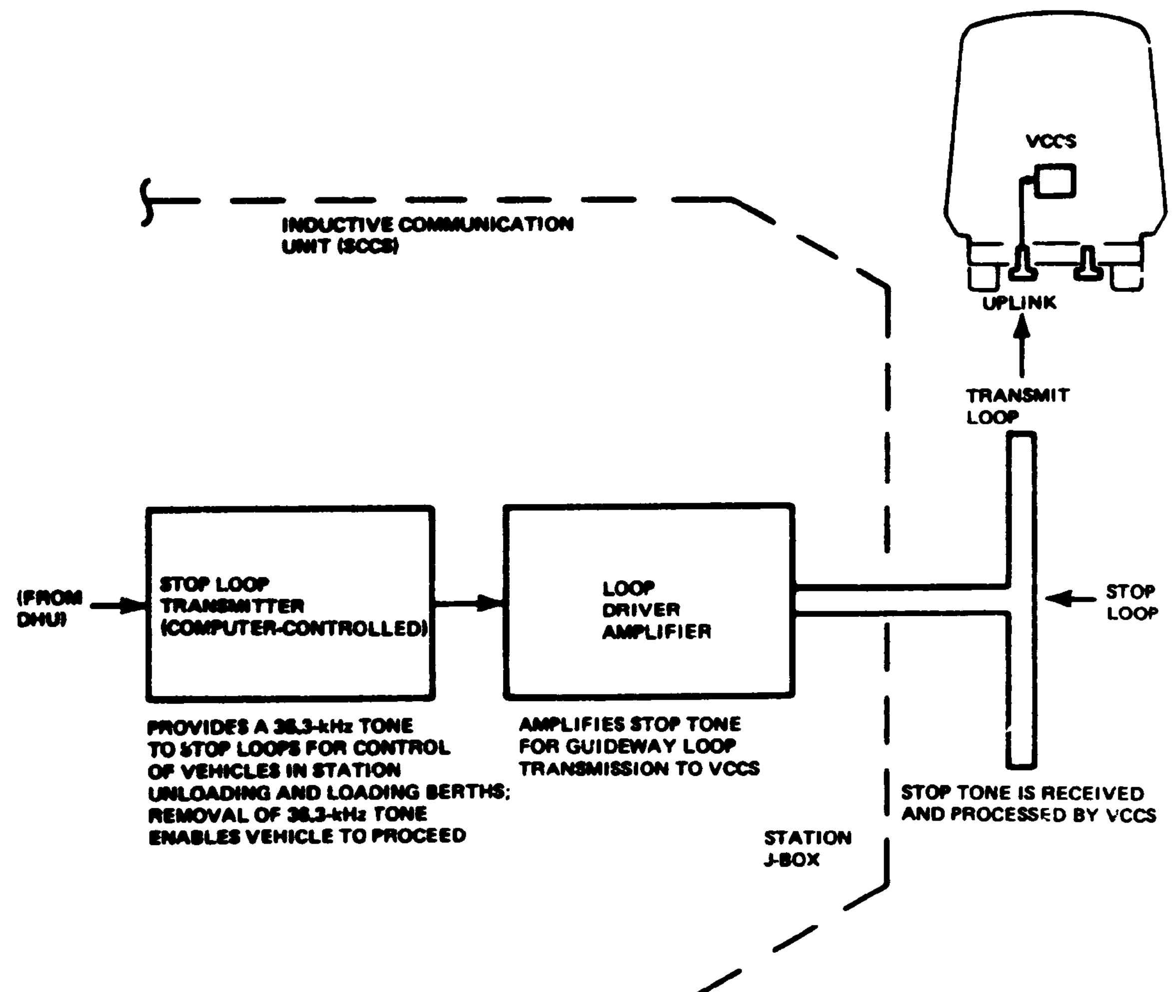


Figure 2-4. Stop Tone Loop Control (Phase IB)

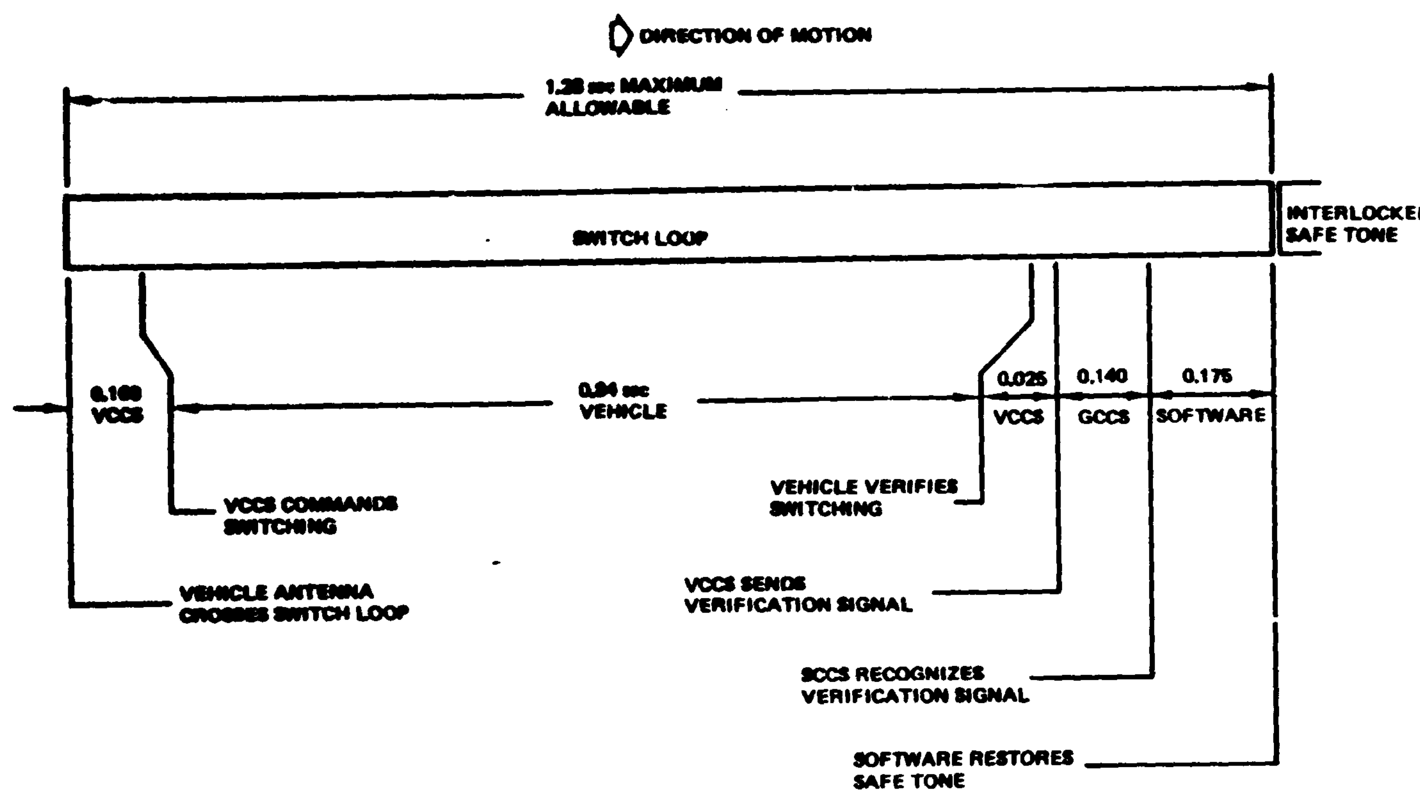


Figure 2-5. Switch Time Allocation Requirements Summary (Maximum Values)

the associated switch loop. Figure 2-6 shows the functional block diagram of the switch tone control units.

The computer-controlled switch tone transmitter receives computer-generated commands that are decoded by the DHU to provide a control data signal and a strobe pulse input to the switch tone transmitter control logic. A logic "1" in the data will provide a chopping frequency of 50 Hz to chop the 28.3-kHz switch tone frequency, while a logic "Ø" will provide a 70-Hz chopping frequency. The 50-Hz chopping signal is used to command a "steer right" and the 70-Hz signal commands "steer left." The output of the transmitter card feeds the loop driver, which drives the associated loop.

The tone generators used for fixed steering commands are simpler and use a 28.3-kHz oscillator hardwired to a 50- or 70-Hz chopping oscillator. This transmitter card then feeds a loop drive and the associated "fixed right" or "fixed left" loop.

Safe Tone Collision Avoidance System (CAS). CAS is independent of the primary control systems of the SCCS. The fail-safe CAS unit is responsible for overriding all controlled vehicle movements along the entire guideway network to prevent collisions by ensuring that vehicles are separated by safe emergency stopping distances. The CAS is a hardwired check-in/check-out processing unit that controls an inductive safe tone output to the vehicle. The vehicle must receive a safe tone to proceed; lack of tone sets the vehicle's emergency brake. The guideway network is segmented into blocks (safe tone loops) with dual hardware/software presence detectors located at the end of each loop for vehicle detection. The presence detectors are activated by magnets located on the vehicle that initiate two logic paths. One logic path interfaces with the station computer (software), and the other logic path consists of the hardware CAS circuitry. A disparity detector compares signals from each of the dual CAS logic paths and removes the safe tone on the loops if the logic paths disagree. A functional diagram of the system is shown in figure 2-7.

Normally "off" and normally "on" logic is used in all other areas. In the normally "on" logic sections of the guideway, the vehicle encounters a loop and activates the presence detectors, causing the logic to remove the safe tone from the trailing

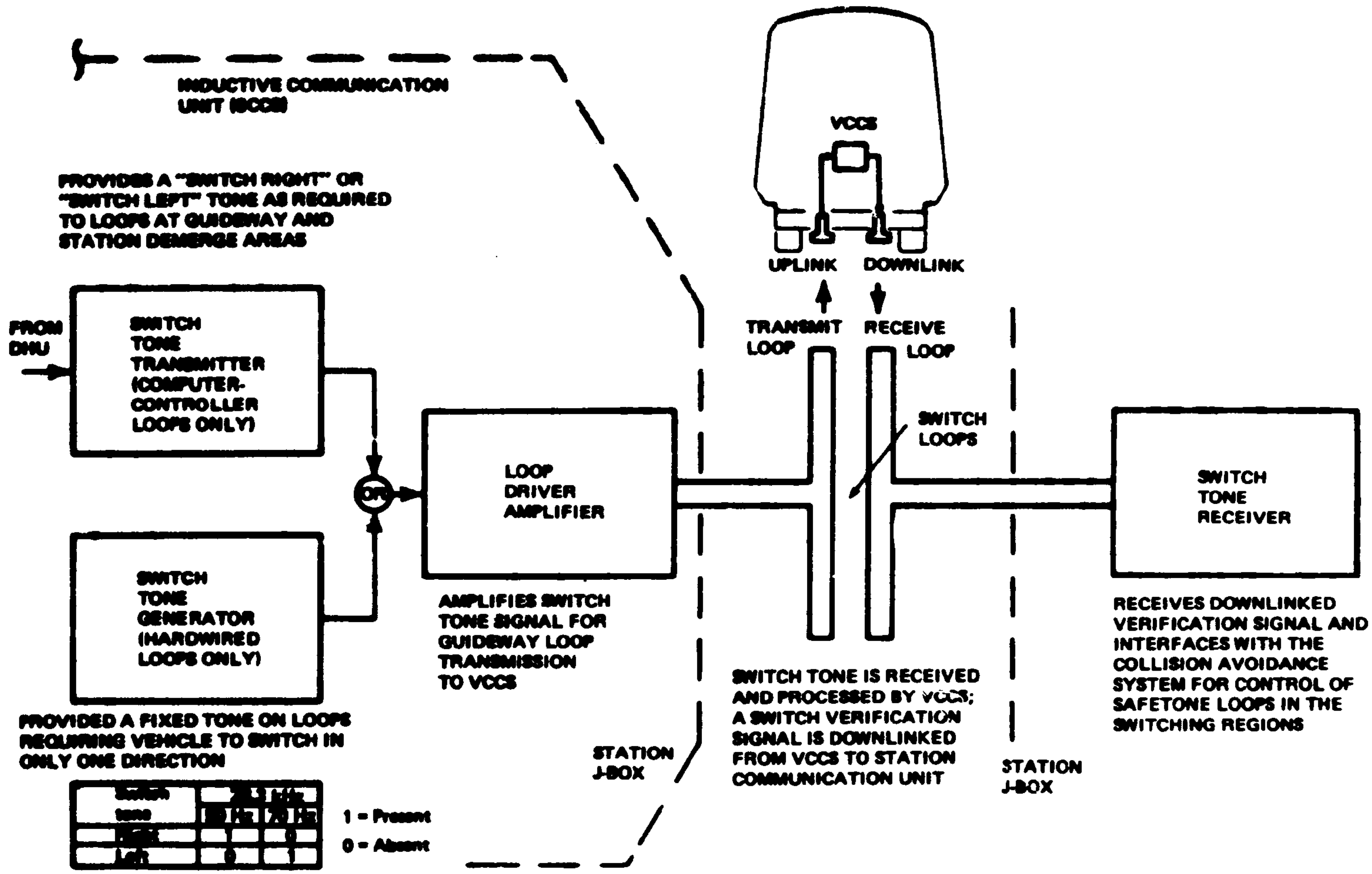


Figure 2-6. Switch Tone Loop Control (Phase IB)

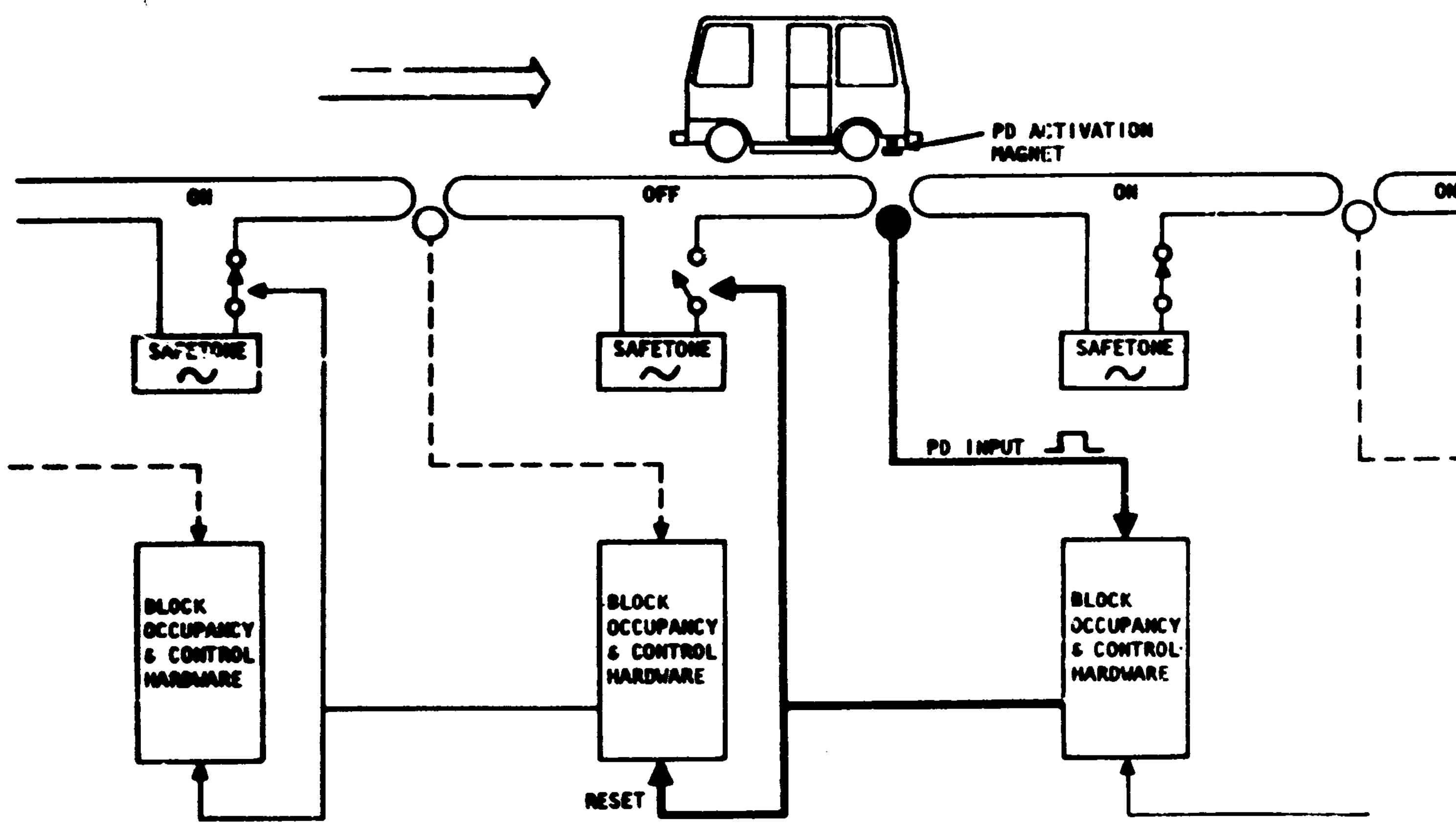


Figure 2-7: CAS Block Control Concept

loop being vacated by the vehicle. This provides an "off" safe tone behind each vehicle to ensure against a collision from a trailing vehicle. In addition to this logic, a normally "off" safe tone loop is provided at the exit of all switch loops and at all merges. This switch loop interlocked safe tone is turned on when the vehicle verifies switching. The merge safe tone is activated to allow only one clear path through the merge. This is collision protection in the event that two vehicles are contending for the same guideway point.

The actual safe tone is generated for an entire station by a safe tone master oscillator generating a carrier frequency of 10.2 kHz. Unlike the other control tones, a modulation is not applied at this point. The 50-Hz chopping frequency is generated at a master oscillator located in the central control facility and fed to a slave oscillator card in each station. The 50-Hz then is routed in a series manner (fig. 2-8) through the various disparity detectors and the zone disparity latch. It then is routed to a special safe tone loop driver that both applies the chopping and provides the drive current resulting in a 10.2-kHz, 50-Hz chopped, unbalanced safe tone signal being fed to the appropriate loop. Thus, when a control gate is turned on, the 50-Hz chopping is applied to the safe tone carrier, and when the gate is turned off, the chopping is removed.

2.2.2 Downlink Communications

Vehicle FSK Downlink. The vehicle downlinks an FSK message in the same format as the station uplink, using a start bit, 16 bits of data, a 16-bit complement, and a stop bit. The bit rate is 1,000 Hz, the "1" frequency is 104 kHz, and the "Ø" frequency is 96 kHz. The vehicle FSK downlink is received by the FSK receive loop and routed through a twisted, shielded-pair feedline and then to the station receiver card. The received signal is applied to two amplifier stages and a bandpass filter, which removes any extraneous crosstalk signals appearing on the receiving loop antenna, and finally to a limiting amplifier that shapes the input signal prior to application to the 96- and 104-kHz notch filters. These narrowband filters allow only the 96- or 104-kHz gated signals to pass, which are then converted to a serial data bit stream.

Switch Verification. When a vehicle has successfully switched in response to a command from a switch loop, it downlinks a switch verification signal which

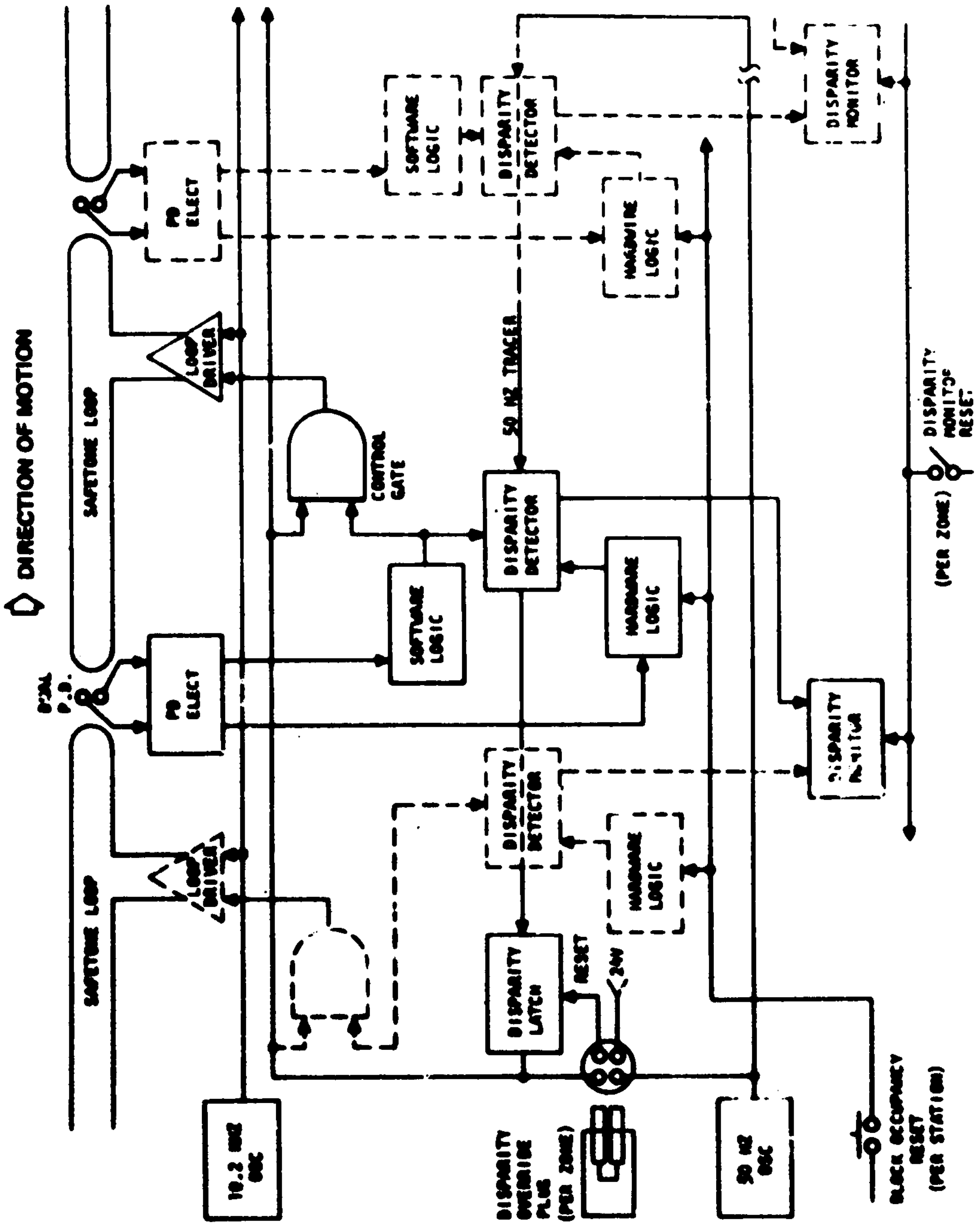


Figure 2-9. CAS Functional Diagram

is a 22-kHz signal chopped at either 50 or 70 Hz corresponding to the chopping frequency of the uplink command. The signal is received by the switch verification loop and processed in the station verification receiver. In the receiver, the signal is applied first to a limiter then to a push-pull amplifier and two emitter follower circuits before being applied to the 22-kHz bandpass filter. The bandpass filter removes any crosstalk appearing on the input line. The signal is then applied through 50- or 70-Hz narrowband filters and another emitter follower, then to a detector-rectifier circuit that detects the modulation envelope (50 or 70 Hz) of the input signal. This 50- or 70-Hz signal is amplified and applied to a pulse-shaping Schmitt trigger circuit and then transmitted to the CAS equipment.

2.3 GUIDEWAY SUBSYSTEM

2.3.1 Guideway Layout and Construction

The guideway structure is a limited-access route connecting the MPM stations and the maintenance facility. Approximately 65 percent of the present guideway is elevated; the remainder is at ground level. The running surface is concrete and contains distributed piping for guideway heating to allow all-weather operation. Steering and electrical power rails are mounted beside the guideway. Emergency walkways, handrails, and guideway lighting are provided for passenger safety if egress is required. Figure 2-9 shows a cross section of an elevated portion of the guideway. Positioning the steering rail near the running pads becomes the critical factor in vehicle antenna tracking as will be discussed later.

Inductive communications loops are installed in slots on either side of the guideway, just inside the running pad. The slots are located such that their centerline will correspond to the antenna tracking centerline of the vehicle. Two parallel slots 6-in. apart are required for each set of loops (uplink and downlink). Slot depth is selected such that the maximum number of loops required will fit without protruding above the guideway surface. Once loops are installed, the slots are filled with an epoxy compound to provide some measure of physical and environmental protection. In the phase IB system, the loop termination resistors also are buried for all loops except the safe tone loops. Unfortunately, this provides a severe environment for the termination resistor. In the phase II portions of the guideway,

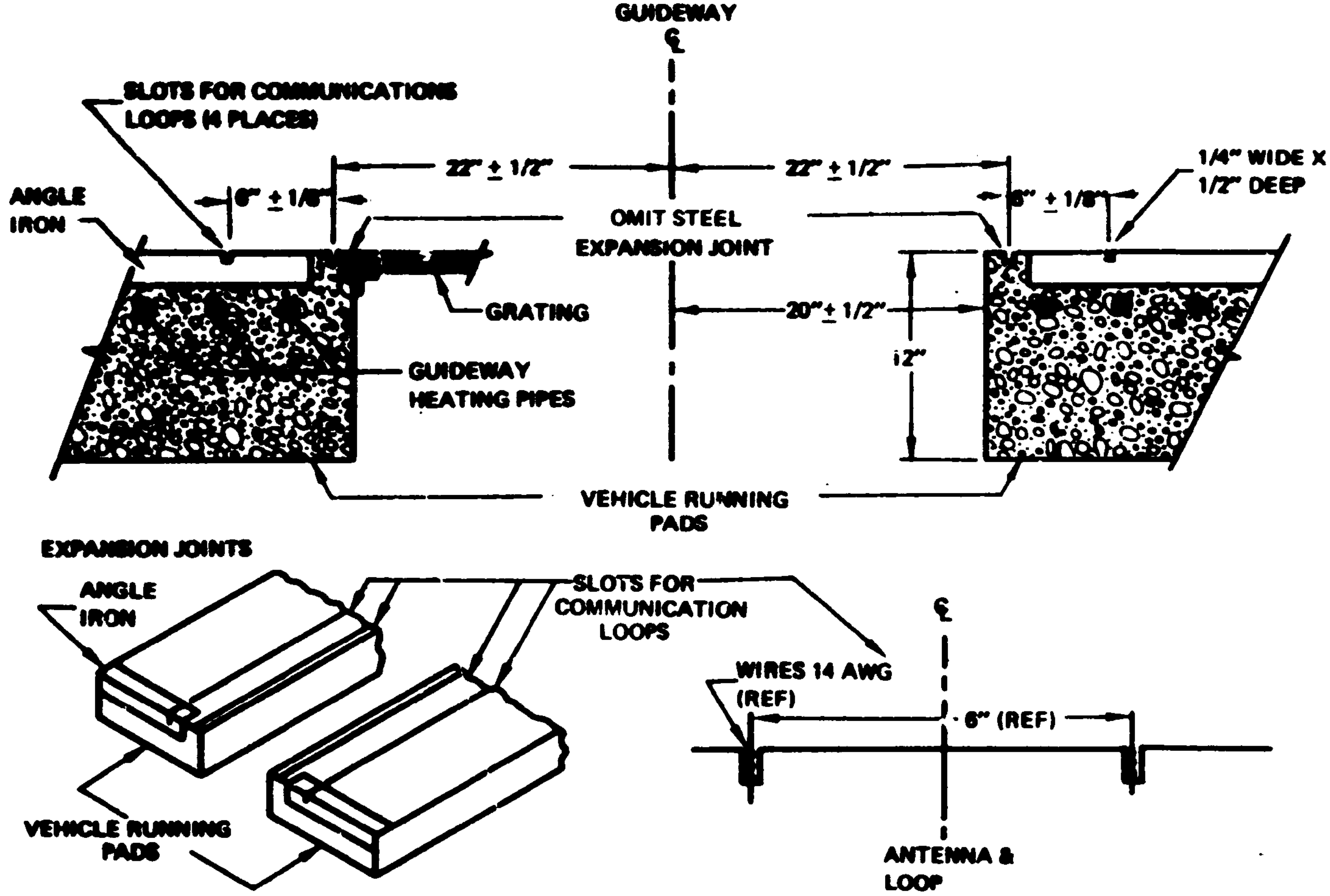


Figure 2-9. Typical Vehicle Running Pads — Elevated Guideway

the resistors have been located in the cable tray with no detrimental effect on the signals.

2.3.2 Inductive Communications Loops

As previously mentioned, the inductive communications loops are located in parallel slots just inside the running pads (see fig. 2-10). Uplink loops are located on the right side of the guideway (as viewed looking in the direction of motion), and downlink loops are on the left side. In the uplink slots, there are a minimum of two loops (safe tone and FSK) in all areas of the guideway. In station berthing areas, a third loop is added for stopping. At merges and demerges, a third loop is added for switch information. Calibration loops form a third loop at certain intervals, and there is the possibility that a calibration loop could occur near a merge or demerge thus placing a switch tone loop in the slot also. Thus, a maximum of four loops is possible in an uplink slot. The downlink is simpler with a maximum of two loops. There is always an FSK receive loop, and a switch verification loop is added opposite the uplink switch command loop at merges and demerges.

In all areas of the track, both uplink and downlink, the loops must be balanced against each other to reduce crosscoupling and feedthrough to an absolute minimum. In areas where only one loop exists, it is advisable to add crossovers at certain intervals to improve the noise rejection of the loop. To balance multiple loops, crossovers are added to reverse the phase of one or the other loop. The crossover locations are selected such that the net coupling from one loop to the other is zero. To further complicate matters, the calibration and stop tone loops may not contain crossovers, as this would degrade the calibration and stopping accuracy. Thus, all balancing must take place in the safe, switch, and FSK loops.

2.3.3 Vehicle

The MPM system uses rubber-tired vehicles. Each vehicle has ten major subsystems: passenger module, environmental control unit, chassis, hydraulics, pneumatics, electrical power, propulsion, steering, braking, and vehicle control and communications system. This report is concerned primarily with the latter subsystem.

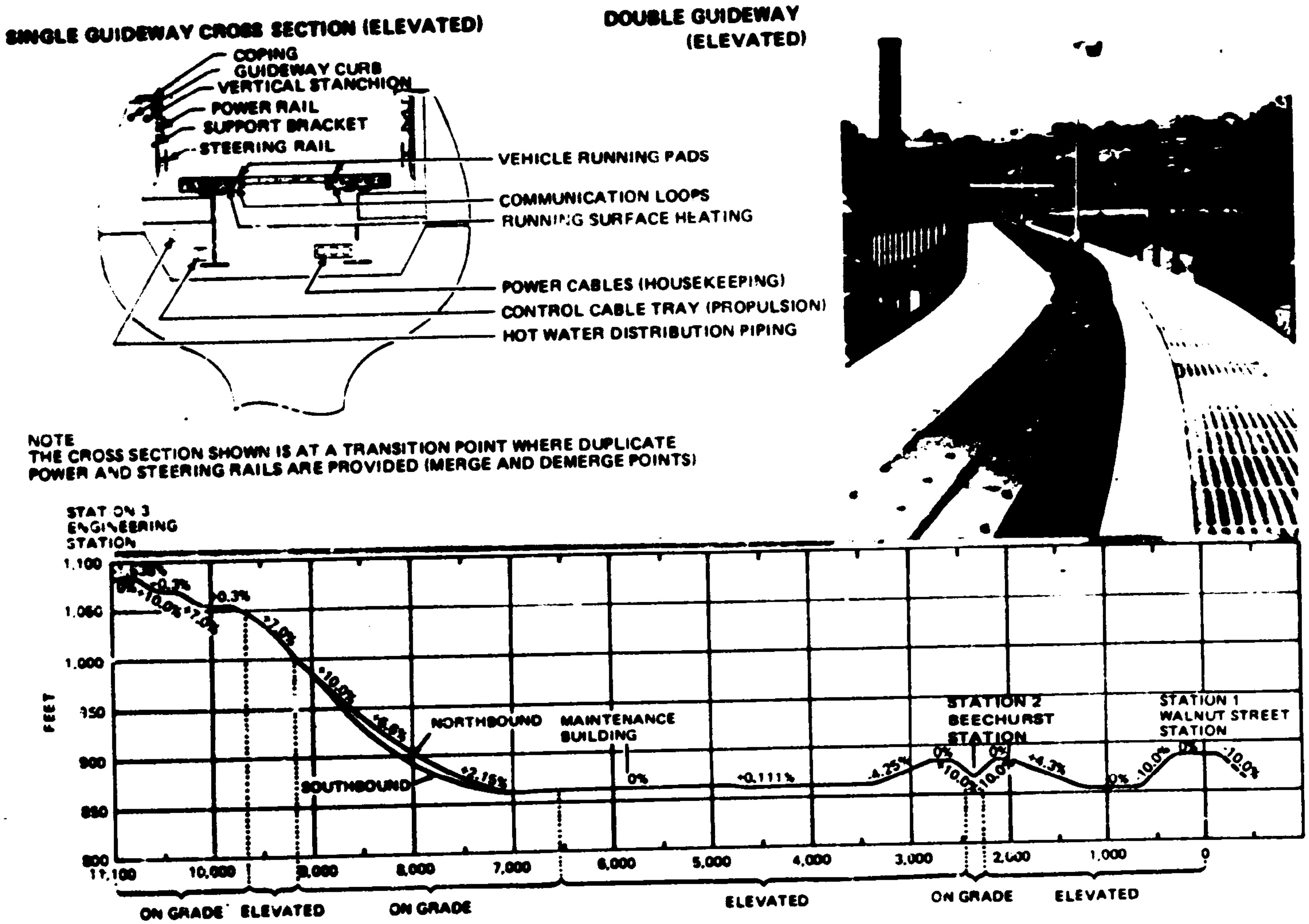


Figure 2-10. MPM Guideway (Phase I)

Commands are transmitted to the vehicle from buried communication loops through antennas located on the underside of the vehicle and routed to the Vehicle Control and Communications System (VCCS). The commands operate the vehicle motor, brakes, steering, and doors. Three-phase 575v power is supplied to the vehicle through power rails, which can be located on either side of the vehicle, and picked up via a power collector arm extended from the vehicle on the steering side. Guide wheels located on both sides of the vehicle extend and contact a steering rail which then is followed until the vehicle is commanded by a switch tone to steer on the other side for a merge or demerge. The guide wheel controls a hydraulic, four-wheel power steering subsystem. The pneumatic system provides an automatic vehicle-leveling control and extends the power collector arms to contact the guideway power rail. The redundant four-wheel disc brakes are hydraulically operated in response to input commands from the VCCS. Normal door operation is electrical in response to input commands from the control and communications system via the FSK uplink. Figure 2-11 shows characteristics of a phase IB vehicle.

2.4 VEHICLE CONTROL AND COMMUNICATIONS SUBSYSTEM (VCCS)

The VCCS is located in the rear of the vehicle above the environmental control unit (ECU). The VCCS is that portion of the C&CS that is carried on board the vehicle (shown in fig. 2-12). The VCCS receives uplink commands, provides control commands to the vehicle, and identifies and transmits downlink vehicle status to the SCCS. The VCCS responds to guideway inductive communications and vehicle inputs to regulate vehicle speed and generate control functions for the vehicle. The VCCS regulates vehicle speed and position throughout the entire guideway network as well as controlling vehicle doors, brakes, and switching functions.

The VCCS also provides commands to the vehicle to ensure safe operation. An overspeed detector commands emergency rate braking when the vehicle exceeds the safe tolerance on the commanded guideway speed. The VCCS also applies emergency brakes when it senses loss of safe tone from the inductive communications system. The VCCS monitors the status of the vehicle, and if an unsafe condition is detected it stops the vehicle and transmits a message via the FSK link to the station and then on to the central system operator.

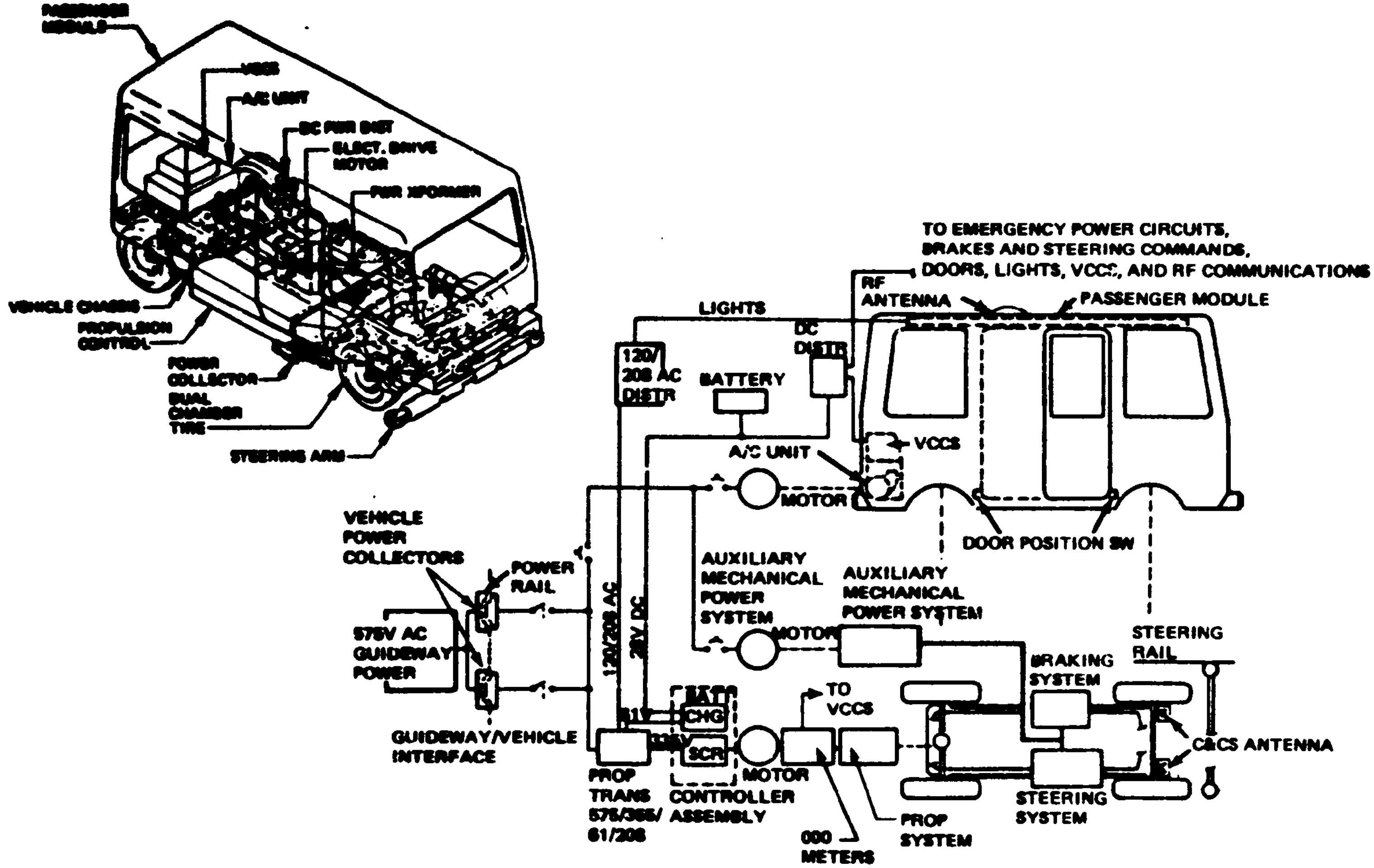


Figure 2-11. Vehicle Characteristics (Phase I)

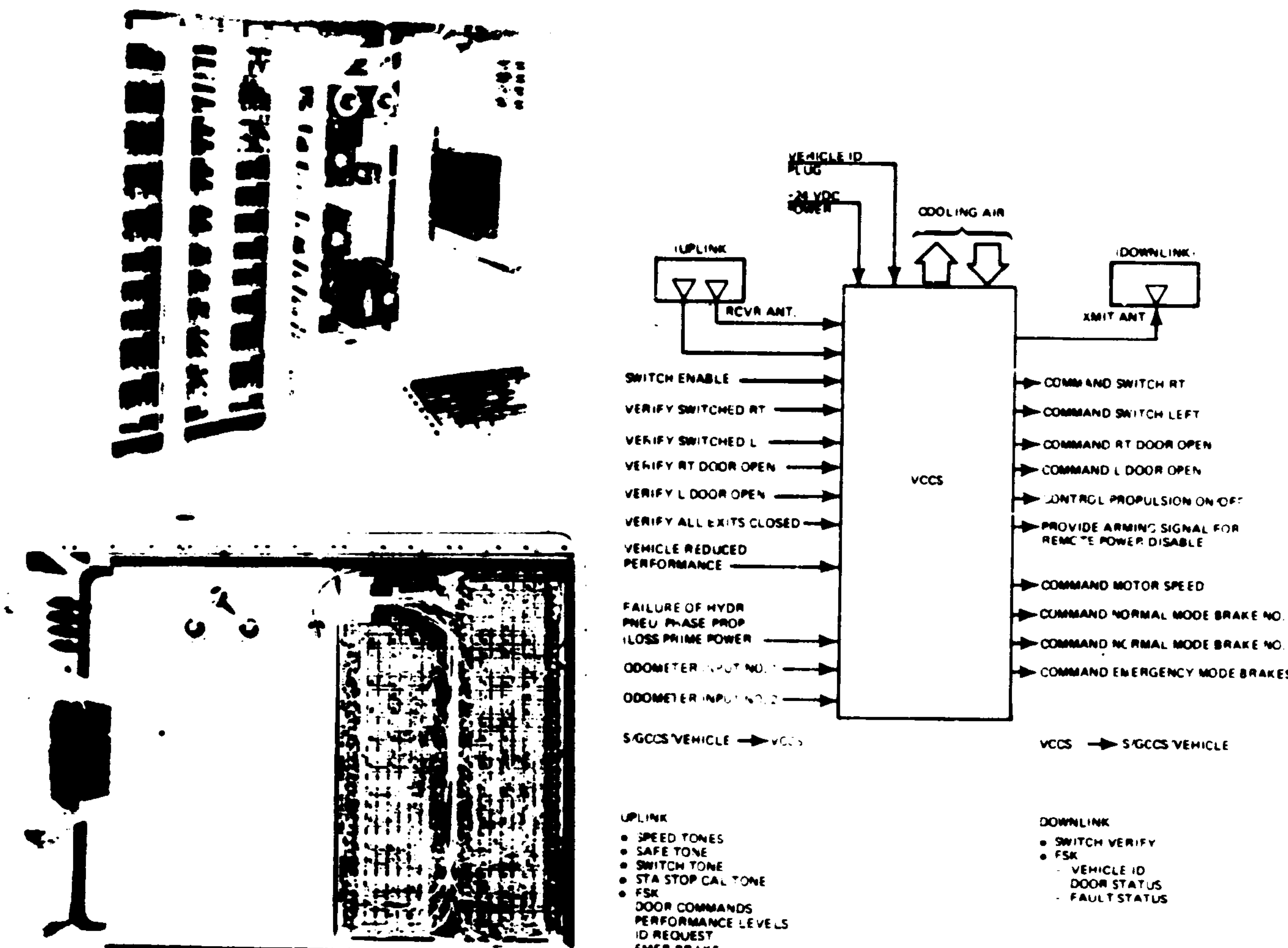


Figure 2-12. Vehicle C... trol and Communications Unit

The VCCS is composed of the following functional units: antennas, communications unit, data handling unit, control unit, and support unit.

This report is concerned only with the antennas and communications unit.

2.4.1 Antennas

Two antenna assemblies provide the VCCS with two-way communications with the SCCS through the buried loops. One antenna assembly is used for receiving, the other antenna for transmitting. The antennas are mechanically fixed to the vehicle and electrically linked to the VCCS. The receiving antenna assembly actually contains two antennas (part of the vehicle's redundant uplink system). The antennas are vertically mounted loops in a "bifilar" configuration to reduce interference from external noise sources such as vehicle power surges. The transmit antenna is a single horizontal rectangular fixture with multiple turns of a small conductor wire. The receive antenna is located on the right side of the vehicle and the transmit on the left. Both are located in the forward portion of the vehicle about even with the front axle, suspended 1-1/8 in. above the guideway.

2.4.2 Communications Unit

The communications unit of the VCCS consists of a downlink transmitter and dual redundant uplink receiver circuitry to provide signals to and receive signals from the guideway. Uplink communications consist of FSK messages, safe tone, switch tone, stop tone, and calibration tones. Downlink communication is an FSK status message and switch verification tones verifying the response of the vehicle to a switching command. A VCCS functional block diagram is shown in figure 2-13.

Civil Speed Receiver. Guideway civil speed tones are transmitted to the vehicle through the use of three signal frequencies: 6.1 kHz (speed tone A), 13.3 kHz (speed tone B), and 17.2 kHz (speed tone C). Each of the speed tones is chopped at a 50-Hz rate. Where two tones are present, in the higher speed areas, the tones are alternately chopped such that the tones are not present simultaneously.

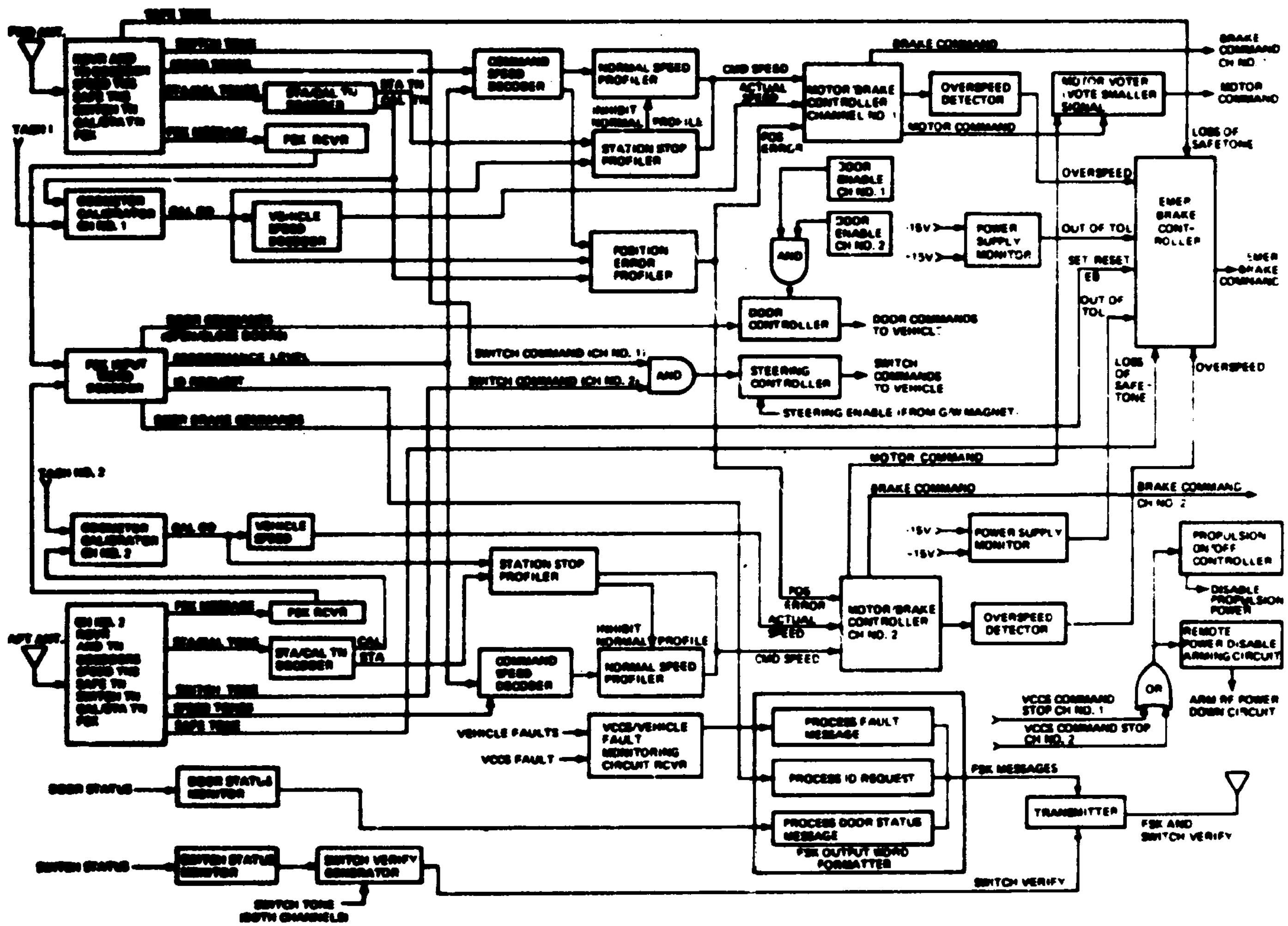


Figure 2-13. VCCS Functional Block Diagram

The frequency versus civil speed assignments are such that two tones are required to specify the higher civil speeds (22, 33, and 44 ft/s). Should one tone fail, the civil speed thus specified will be a lower speed (4, 6, or 8 ft/s). The presence of three or more tones or the absence of any assigned tone is an abnormal condition, and the system will default to the lowest civil speed, 4 ft/s. The speed tone receivers are capable of detecting these speed tones and the 50-Hz modulation and of producing a logic level output in less than 70 ms. On loss of the speed tone or its 50-Hz modulation, the receiver will reset the speed enable function in less than 115 ms.

Safe Tone Receiver. A safe tone is transmitted to the vehicle with a tone frequency of 10.2 kHz. The tone is chopped at a 50-Hz rate, as described for the speed command receivers. The safe tone receivers are capable of detecting the safe tone and the 50-Hz modulation and producing a logic output in less than 70 ms. Upon loss of the safe tone or its modulation, the receiver will reset the logic level in less than 115 ms.

Steering Tone Receiver. Steering tones are transmitted to the vehicle with a 28.3-kHz signal frequency. The "steer right" command will chop the 28.3 kHz at a 50-Hz rate, and the "steer left" command will chop the 28.3 kHz at a 70-Hz rate. The steering tone receiver is capable of detecting the 28.3-kHz signal and chopping frequency and producing logic level outputs to indicate that a "switch right" or a "switch left" command has been detected. The steering tone receiver also will provide the 50-Hz and 70-Hz chopped frequencies separately to the steering control circuit for use in generating the verification downlink. The VCCS will generate a steering command in less than 100 ms from the time the signal appears at the antenna. This includes receiver acquisition time, false detection time, and the time required by the steering control circuit. Loss of steering tone or its modulation at the receiving antenna will be detected within 250 ms. The receive and detection circuitry is such that no spurious steering commands will be generated.

Calibrate/Station Stop Receiver. This receiver detects and demodulates the signals sent to the vehicle, via the guideway loops, for odometer calibration and station stopping. The signals sent to this receiver to initiate the stated functions share a common carrier frequency of 36.3 kHz. The calibration/station stop receiver is capable of detecting the 36.3-kHz signal and producing a logic level output in less than 15 ms. Upon loss of the 36.3-kHz tone, the receiver will reset the logic level in less than 15 ms. The station stop and odometer calibration signal tones are differentiated in the station stop control. The 4-ft/s civil speed command and detection of the 36.3-kHz signal indicate a station stop function; detection of the 36.3-kHz signal and the absence of the 4-ft/s civil speed command indicate a calibrate function.

<u>FSK Receiver</u>. This receiver detects and demodulates uplink FSK messages and produces a logic level output message corresponding to the transmitted FSK message. The guideway-transmitted FSK uplink message consists of a 34-bit word using 121 kHz and 129 kHz to represent the data "Ø" and the data "1", respectively. Two FSK receivers are provided; one operating from the forward receive antenna and one operating from the aft. Each receiver provides two output logic lines representing the data levels. The logic "1" lines from each receiver are "or-ed" together as are the logic "Ø" lines to increase the probability of receipt of an FSK message.

<u>Transmitter</u>. The VCCS transmits FSK downlink information and switch verification information to the guideway receive loops. The FSK downlink message is substantially the same format as the uplink message with the exception that the data "Ø" frequency is 96 kHz and the data "1" is 104 kHz. This reduces the possibility of uplink/downlink interference. The steering verification signals consist of a 22-kHz carrier frequency chopped by the 50 or 70 Hz previously derived from the switch command to indicate the vehicle has switched right or left, respectively. Both FSK and switch verification signals are transmitted to the downlink loops from a single vehicle antenna.

3. INDUCTIVE COMMUNICATIONS DESIGN EVOLUTION

To properly set the stage for a discussion of the Inductive Communications System (ICS) design evolution, it is pertinent to present some of the early conceptual trades. The trades presented in section 3.1 led to the formulation of the basic inductive communications system implemented in phase IA and later modified in phase IB and phase II. Because of the accelerated schedule under which the design was accomplished, a complete early history is not available. What is presented here comes from early design memos and a Johns Hopkins University control concepts study done for JPL. Section 3.2 presents the resulting Morgantown ICS system and discusses evolution of each subsystem design from phase IA through phase IB and phase II. First there is a discussion of the phase IA considerations and problems and then a presentation of the resulting phase IB baseline and related problems. This is followed by the phase II design modifications and, where applicable, the phase II Seattle Transportation Test Facility (STTF) and system integration laboratory (SIL) test results. The guideway link model (i.e., ICS loop driver-to-VCCS input) development and its use to provide ICS performance predictions and design parameters are presented in section 4. A summary of ICS design recommendations is presented in section 5. for the benefit of any future inductive communications users.

Since a discussion of the ICS design evolution through three phases covers considerable material a chronological overview (shown in fig. 3-1) is presented below for convenience.

In September 1970, the Jet Propulsion Laboratory of Pasadena, California, was selected as system manager. In conjunction with this responsibility, JPL began a series of preliminary design studies and trade-offs, ending in July 1971 with the selection of an inductive communications concept rather than contact wires, leaky coax and waveguide, or conventional radio. In May 1971, the Bendix Corporation of Ann Arbor, Michigan, was awarded a contract for design and fabrication of the control and communications system (C&CS). By July 1971 guideway schematics were complete (JPL) and C&CS design was well under way (Bendix). In August 1971 UMTA replaced JPL with The Boeing Company of Seattle, Washington, as system integration and management contractor (in addition to the vehicle

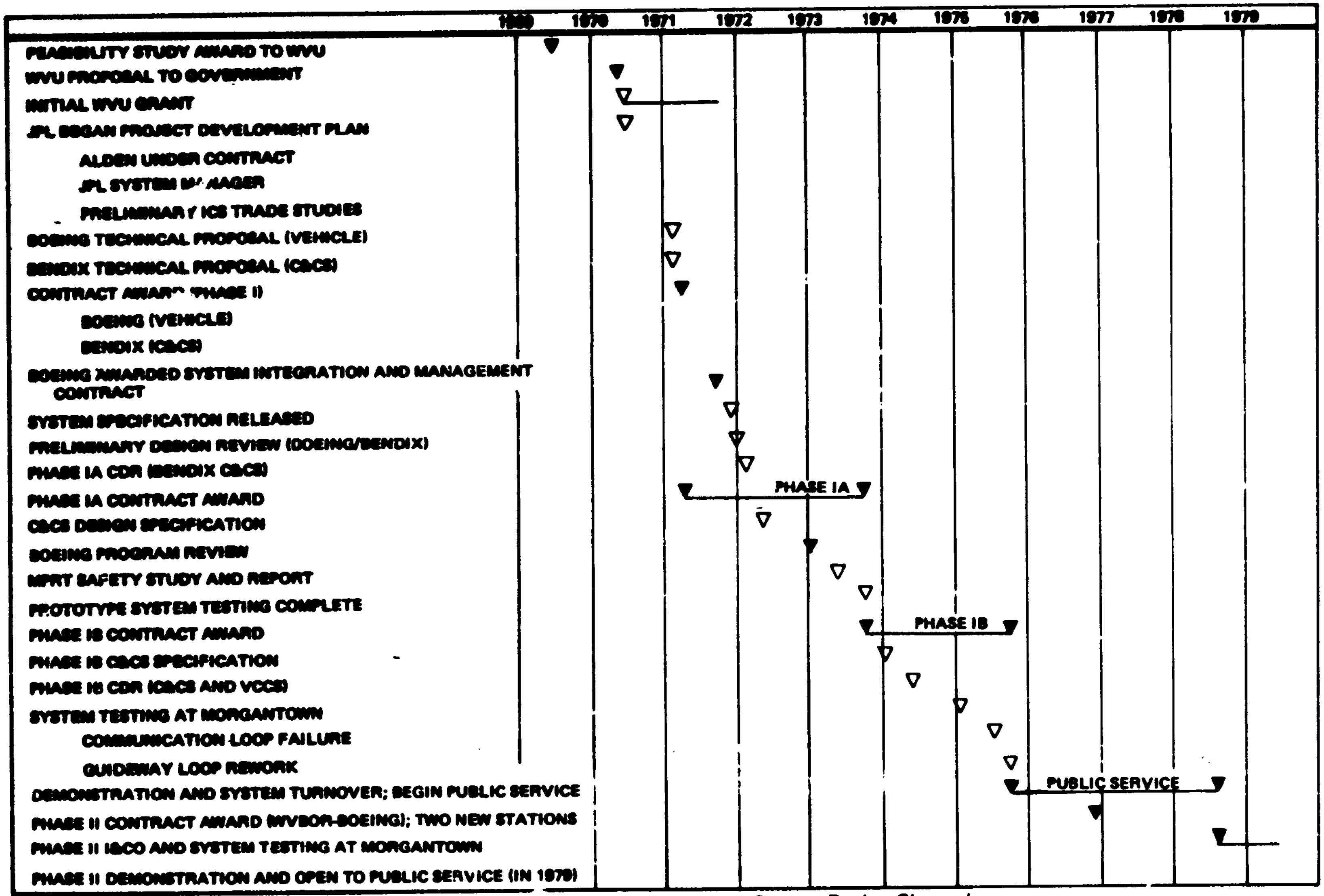


Figure 3-1. C&CS Inductive Communications System Design Chronology

design and fabrication contract previously awarded Boeing in May 1971). After several variations in system configuration were evaluated, it was determined that a three-station system would be built in several phases.

The first, phase IA, was to be a test and demonstration phase concluding in September 1973; the second, phase IB, was to produce a full system to go into passenger operation in 1975. After the phase IA demonstration in October 1972, it was evident that several design changes were needed in the inductive communications system. These were incorporated into the phase IB contract, with Bendix being responsible for the engineering and fabrication and Boeing being responsible for the design integration and certain retrofit tasks to incorporate Bendix engineering. As design integrator Boeing was to undertake certain control and communication engineering tasks; specifically, an electromagnetic compatibility plan, a C&CS requirements analysis, and an inductive communications study. The purpose of the inductive communications study was to further define the link, make recommendations for design changes, and set recommended signal levels and margins. Boeing was also directed to design and implement a new Vehicle Control and Communication System (VCCS) based on the results of the above study. This unit was previously built by Bendix.

During C&CS installation and checkout of the phase IB ICS, Boeing encountered communication problems that necessitated further changes to the phase IA guideway, the station electronics, and the new VCCS. The changes included guideway modifications to replace bad splices and improve reliability, correct expansion joints, correct erroneous crossover locations, and reduce crosscoupling at merges and demerges. The steering rail alignment was changed to correct vehicle off-tracking. Station and VCCS changes were to improve signal magins and provide additional noise immunity. These changes were incorporated and in September 1975, after a demonstration, the system was opened to passenger traffic. During the nearly 3 years the system has been operational, availability rose from a low of 85 percent after turnover to an average of greater than 99 percent in 1978.

To fulfill the University's original requirements, two new stations were required to link the Medical Center and the Towers dormitories to the operational system. In November 1976, a phase II contract was awarded to Boeing to complete the remainder of the system. During the phase II design, the VCCS remained essentially unchanged while major changes were made to the guideway loops and station electronics going into the new portions of the system. Phase II changes were made to lower system costs (both fabrication and maintenance) and to improve C&CS reliability. In conjunction with the phase II design, a communications data base study was undertaken to further define link parameters, set new signal margins and loop drive requirements, and assemble a final detailed assessment of link losses.

3.1 DESIGN EVOLUTION—GENERAL

As stated, the purpose of this report is to document and discuss the design evolution of the Morgantown Inductive Communications System. To this end some of the data contained in this report was derived from sources outside of The Boeing Company. Early ICS design and analysis was done by the Jet Propulsion Laboratory (JPL), data detailing this stage of the evolution was derived from JPL memos and reports which are a part of the program records, and outside studies, such as The Johns Hopkins University report, which were contracted for by JPL. In addition, work done by The Bendix Corporation, the C&CS subcontractor, is also included. Information from these sources is included in the spirit of completeness and continuity; no attempt has been made to verify the accuracy or justify the rationale of work done by other contractors.

3.1.1 Communications Concepts

In an early JPL design memo five various communication links applicable to Morgantown were considered; direct contact wires (both dedicated and shared with power), low-frequency inductive loop, high-frequency leaky coaxial cables, microwave leaky waveguide, and radio. The advantages and disadvantages of these concepts were weighed as follows:

a. Direct contact wires (table 3-1) were felt to provide the tightest coupling of signal power with lowest interference to and from external environment. Crosstalk from section to section would be a costly problem because of the segmented nature of the Morgantown concept. A shared wire concept (power and signal) (table 3-2) was considered also. The major weakness was brush noise created by contact bounce. JPL stated, "Since the contact bounces create interference and cause vital data dropouts, this link is seldom considered a serious candidate for computer controlled transportation systems."

b. An inductive transmission link (table 3-3) was considered, which utilized "close inductive coupling of a loop coil to an open wire carrying messages." It was stated at that time that inductive communication systems had been installed and demonstrated successfully in the United States and abroad; the Allegheny and Japan NTL systems were used as examples. The link was felt to be simple, installed at reasonable cost, and flexible from the standpoint of sectionalization. The disadvantages stated were higher susceptibility to electromagnetic interference than the direct contact system and the potential of radiating interference to the outside environment (must be kept within FCC limitations). The use of a narrowband system or spread spectrum technique was postulated as a solution to the above.

c. Leaky coax (table 3-4) was also considered for the communications link. The advantages were adaptability to sectionalized system and low noise susceptibility. Disadvantages were cost, signal strength variations, high attenuation (25 dB per 5/8 mile), and loose coupling; and, most important, this report stated that "no existing systems were known to employ this data transmission scheme."

d. Similar to the above concept, leaky waveguide (table 3-5) was considered. Advantages are similar to leaky coax although attenuation is less severe (4 dB per 5/8 mile). Disadvantages were less adaptability to sectionalized control and more costly installation and transmitter and receiver design; and, as with the above, there were no existing systems in operation at the time of the trade.

e. Lastly, a radio link (table 3-6) was considered. This form of link was advantageous because of the centralized control concept and the lower installation costs. Disadvantages were unsuitability for sectionalized control, loose coupling, deep nulls in signal strength, and high interference potential due to the large number of vehicles.

TABLE 3-1 ADVANTAGES AND DISADVANTAGES FOR DIRECT CONTACT WIRE TRANSMISSION LINK-DEDICATED WIRES FOR DATA SIGNALS (JPL TRADE STUDY-FEBRUARY 1971)

ADVANTAGES	DISADVANTAGES
1. Tightest coupling to data signal power.	1. Additional wire costs for data required.
2. Independent layout for communication and power distribution sections.	2. Noise due to brush contacts.
3. Less interference to external environment.	3. Momentary data dropout.
4. Less coupling to interference.	
5. Coupling from power line interference somewhat controllable.	

TABLE 3-2 ADVANTAGES AND DISADVANTAGES FOR DIRECT CONTACT WIRE TRANSMISSION LINK-SHARED POWER TRANSMISSION WIRES (JPL TRADE STUDY-FEBRUARY 1971)

ADVANTAGES	DISADVANTAGES
1. No additional wire costs for data.	1. Filters required to separate power and communication signals.
2. Tightest coupling to data signal power.	2. Isolation required between sections to eliminate cross-talk through power distributing system.
3. Less interference to external environment (depending upon self-interference level).	3. Communications and power distributing sections not necessarily the same.
4. Immunity to weather conditions same as the shared power transmission system.	4. Termination for surge impedance harder to control.
	5. Tightest coupling to self-interference.
	6. Additional noise due to brush contacts.
	7. Momentary data dropout.
	8. More communication power required than dedicated wires.

TABLE 3-3 ADVANTAGES AND DISADVANTAGES FOR INDUCTIVE LOOP TRANSMISSION ON LINK

(JPL TRADE STUDY-FEBRUARY 1971)

ADVANTAGES	DISADVANTAGES
1. Relatively close coupling.	1. Dynamic envelope of coupling.
2. Free from brush contact noise.	2. Requiring switching to both sides of guideway.
3. Coupling to power line interference controllable by suitable layout.	3. Frequency response limited by pick-up cores.
4. Small leakage of interference to external environment.	4. If wires not protected, possible problem created due to icing (freezing rain).
5. More spectral space permitting coding choice to combat burst errors.	5. Noise spectral density higher at lower frequency range.
6. Low attenuation along the wires at frequencies considered.	
7. Signal power easy to generate and distribute from central points to guideway sections.	
8. Suitable for sectionalized control.	
9. Installation cost reasonable.	
10. Repair and maintenance reasonable.	
11. Tolerance to weather conditions fair.	

TABLE 3-4 ADVANTAGES AND DISADVANTAGES FOR LEAKY CABLE TRANSMISSION LINK (JPL TRADE STUDY-FEBRUARY 1971)

ADVANTAGES	DISADVANTAGES
1. Cable installation at center of roadway permissible.	1. Cable construction more expensive due to slotting.
2. Both separation among different control signals simpler to accommodate.	2. High signal power required due to loose coupling and high attenuation.
3. Higher number of channels available (not required).	3. Signal power slightly more expensive to generate.
	4. Signal variation due to attenuation. Extreme nulls (?)
	5. Potential source of interference in the medium frequency range to external environment.
	6. Possible interference with guideway sensors with center of roadway cable layout.
	7. Problems with weather conditions.
	8. Repair and maintenance difficult.
	9. If downlink required, high power requirement on vehicle transmitter.
	10. Schedule difficult to meet.

TABLE 3-5 ADVANTAGES AND DISADVANTAGES FOR LEAKY WAVEGUIDE TRANSMISSION LINK

(JPL TRADE STUDY-FEBRUARY 1971)

ADVANTAGES	DISADVANTAGES
1. Waveguide installation at center of roadway permissible.	1. Waveguide construction very expensive.
2. Path separation among different control signals reasonable to accommodate if transmitters placed on guideway.	2. High signal power required due to loose coupling.
3. High number of channels available (not required).	3. Signal power expensive to generate.
4. Noise spectral density lower at waveguide operating frequencies.	4. Potential source of ultra-high frequency interference to external environment.
	5. Problems due to weather conditions.
	6. Repair and maintenance difficult.
	7. If downlink required, high power requirement on vehicle transmitter and expensive to generate.
	8. Schedule difficult to meet.

TABLE 3-6 ADVANTAGES AND DISADVANTAGES FOR RADIO TRANSMISSION LINK

(JPL TRADE STUDY-FEBRUARY 1971)

ADVANTAGES	DISADVANTAGES
1. Communication cables not needed.	1. Not suitable for sectionalized control and block control concepts.
2. Centralized operation; no local station control necessary.	2. Individual vehicle addressing required.
3. Relatively independent of weather conditions.	3. Vehicle decoding more complicated.
4. Guideway maintenance of communication links not required.	4. Sensitive to external noise due to loose coupling and antenna size.
	5. Transmitted power under FCC regulation.
	6. Highest leakage of interference to external environment.
	7. Possible nulls in signal level.

This report concluded that ". . . the inductive loop approach is the only scheme that is reasonable." Leaky coax and waveguide were dismissed because at that time they were only experimental and large development costs would be incurred. It was doubted that these systems could be made operational within the tight schedule for the project. The contact wire concept was rejected primarily because of large vehicle brush noise. A radio link was rejected because of its inflexibility for sectionalized control and general reliability and the individual addressing requirement. In retrospect it appears that this concept trade was reasonable and well done, with the exception of a possible hasty dismissal of contact wires. Apparently the proposed Morgantown system was, at that time, assumed to be highly susceptible to vital data dropouts and for that reason the contact wire concept was dropped. As will be seen later, the inductive communication concept also possessed the potential for vital data dropouts (not mentioned in the trade)—a problem later resolved by redundant antennas and vehicle receivers. It appears that after this trade JPL was firmly on the road to development of an inductive communications system.

3.1.2 Inductive Communications Concept Development

Although early developmental data are sketchy at best, we will try to follow some of the important aspects of the inductive communications system through the early conceptual development. Data sources for this section are early design memos and the Johns Hopkins/APL report to be discussed shortly.

Once an inductive link was selected, the placement of the guideway loops and design of the vehicle antenna became primary concerns. Apparently, it was felt that the receive and transmit electronics were well within the state of the art at that time.

3.1.2.1 Interference and Power Distribution

Concern was expressed that there would be significant electromagnetic interference from the third rail (power rails). Early designs showed redundant loops accessible from either side of the vehicle as was the power distribution system. These loops were located vertically along the guideway wall. It was felt that the communication wires should be placed as close together as possible to take maximum advantage of common mode rejection. In a conceptual review of EMC problems, several items were called out as comprising power-system-generated noise; they were internal power conversion noise (SCR or choppers) and current switching in the lines due to contact bounce. Contact-bounce-generated noise was felt to consist of (1) high-voltage gaseous discharge (arcing), (2) high field breakdown (bridging), and (3) change in line current (magnetic induction). The conclusion was that mutual inductance between the power distribution system and the communications circuit should be minimized. From the standpoint of EMI with the communications circuit a "high-voltage, single-phase a.c. power distribution system" was recommended. The final power system design was a 575V, 3-phase system.

3.1.2.2 Antenna and Loop Configuration

Once the power distribution system was selected, attention was given to design considerations pertinent to loop and antenna design. After considering all proposed alternatives, the guideway loops were located on the guideway surface just inside the running pads. The recommended antenna design was a rectangular loop antenna, winning out over a core pickup type. It was to be located either 0.835 or 2.335 in. above the guideway surfaces, depending on the vehicle design and flat tire considerations. The loop and antenna design was to allow for a $\pm$3-in. lateral deflection and a $\pm$0.835-in. vertical variation, when located over 8-in.-wide loops.

A set of preliminary link equations was developed to show the interrelationships of loop width, antenna size, and height, and the effects of loop length and termination. Those equations were idealized and intended to permit power budgeting. Some items singled out for special attention in the preliminary link analysis were the need for proper line and loop terminations to eliminate mismatch, EMI considerations, isolation from the power distribution system, and trade-offs involved in the antenna design.

3.1.3 Communications Link Design Guidelines

The final study, which led to much of the detailed design of the MPRT inductive communications system, was a report by Johns Hopkins University/Applied Physics

Laboratory published in August 1971. Commissioned by JPL for the Department of Transportation, this report was titled "Control Concepts for the Morgantown Project." Our area of concern is the section on the inductive communications link. It covered their recommendations for the link itself, data format, modulation techniques, boundary considerations, and, most important, selection of the communication frequencies and encoding method. The following paragraphs are a summary of the rationale and recommendations of this report.

3.1.3.1 The Link

The physical arrangement for the wayside-to-vehicle inductive communications link was recommended to be a guideway current loop coupled inductively to a vehicle-mounted antenna. It was felt in this report that the operating frequency should be restricted to less than 50 kHz in order to minimize radiation and cross-talk. To accommodate for lateral vehicle motion, it was felt that the geometry of the installation would limit it to below 30 kHz. The lower frequencies would, it was felt, provide a constant signal over the entire loop length without significant standing waves.

3.1.3.2 Data Format

To utilize the link, development of a data transfer scheme was required. Four possible data formats were considered. "One of N tones," the simplest, uses one frequency for each message. "M of N tones," where a combination of one or more tones simultaneously is required to define a given message, allows the possibility of more messages than there are tones. "N-tone binary" uses all tones in a binary format yielding 2^N possible messages. FSK uses frequency shift techniques to transmit serial data messages. Here, two or three tones are used to represent the logical Ø, 1, or idle states, and a serial message of M number of bits would be periodically transmitted. This method allows for a large number of possible messages and the possibility of incorporating error detection and correction methods.

3.1.3.3 Bandwidth/Time Considerations

The four proposed data formats were evaluated for "bandwidth/time considerations" to yield trade-offs between total signal spectrum and equipment complexity. It was stated that: "For the one-of-N tone scheme the number of tones assigned to the communication channel is limited by the finite spectrum of an inductive communications link and the finite bandwidths for each tone." The three-tone FSK data format makes efficient use of the spectrum, but the serial format yields a significantly longer response time than the dedicated one-of-N scheme. It was stated that: "Since each bit of the transmitted message must be long enough to pass through the bandpass filters with reasonable fidelity and an N-bit message requires at least 2^N times the bit time (for return-to-zero format), the trade-off becomes fewer bandpass filters vs. a series addition of response time."

3.1.3.4 Antenna Boundary Considerations

Another consideration that yields a trade-off is the boundary between two loops or signaling segments. Here the choices appear to be between a signal overlap allowing signals from both segments to be received for a period of time and a finite no-signal period. For the one-of-N system, a threshold detector was considered. Such a system, however, would yield an erroneous signal when an overlap is encountered at a segment boundary (due to presence of two signals). A more complex system based on magnitude comparators, it was felt, would eliminate this problem. The segment boundary creates a different problem with the serial FSK system since ". . . a vehicle will generally arrive at the antenna boundary during the transmission of a serial word, and will enter the next region during the transmission of a different word." It was felt the solution would be to "duplicate onboard equipment and use different frequencies in alternating blocks." It should be noted that the final MPM system made use of duplicate antennas and receivers on board the vehicle, while using the same frequencies throughout.

3.1.3.5 Modulation

To ensure that either a steady false tone or no tone causes the system to revert to a safe condition, an a.c. coupling technique was recommended for use. The FSK system, by its nature, satisfies this requirement; however, in the one-of-N system a.c. coupling requires the modulation of the tone by an a.c. signal (meaning a tone of a different, substantially lower frequency). Figure 3-2 shows the a.c. coupling technique proposed in the Johns Hopkins/APL report.

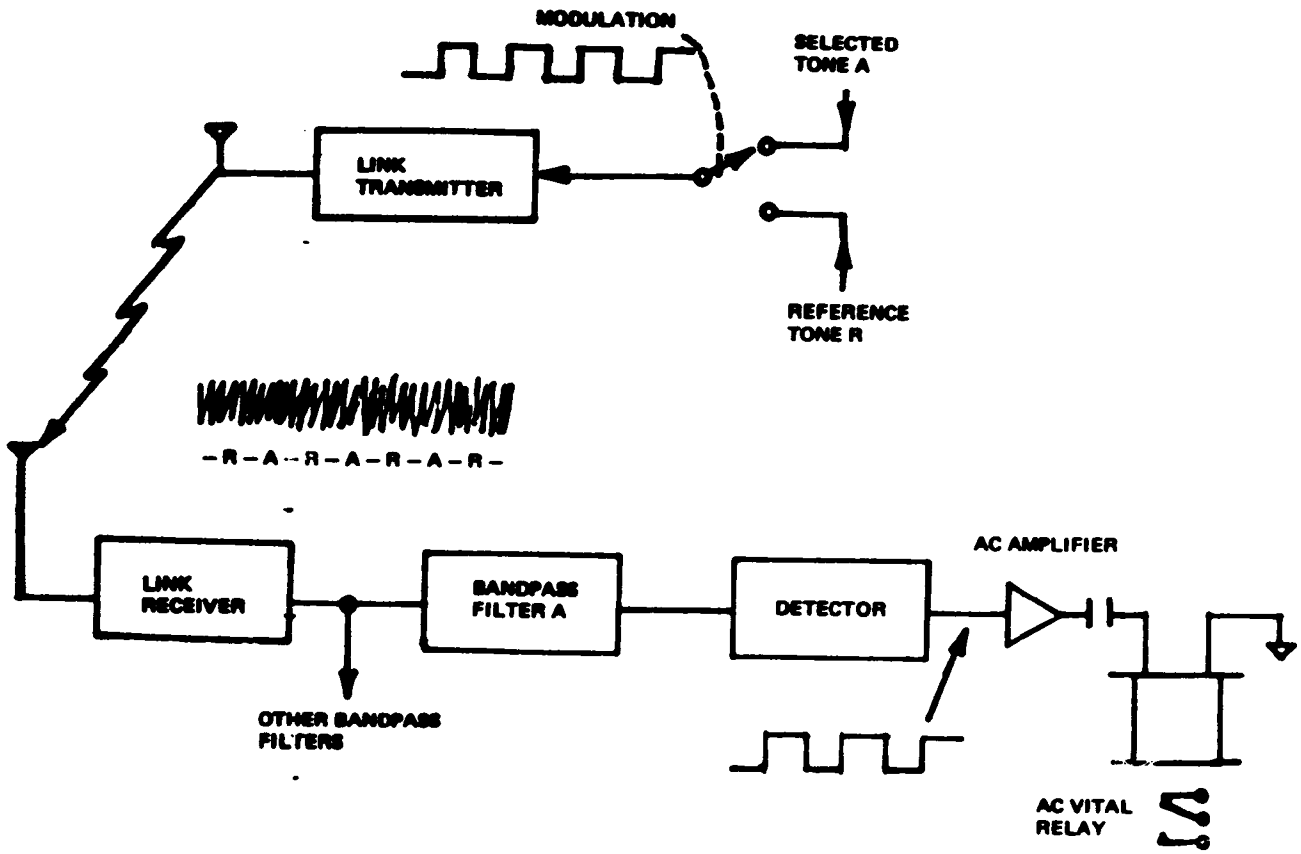


Figure 3-2. Proposed AC Coupling Technique (Johns Hopkins/APL report)

3.1.3.6 Selection of Tones and Format

The a.c. coupling modulation frequency was selected to be 50 Hz (square wave) to yield "tolerable onboard decoding times." Equation (3-1) was developed in the Johns Hopkins study to provide a means of determining adjacent channel separation. The sample calculation presented shows the derivation of channels adjacent to a 22-kHz channel.

For the proposed filter response G

Midband gain = 1

Midband frequency = $\omega_o = \frac{1}{\tau_o}$

For $X = \omega\tau_o$ and $G = \frac{1}{\tau_o}$ at X

$$x^2 = \frac{\left(2 + \frac{99}{Q^2}\right) \pm \sqrt{\frac{99}{Q^2}\left(4 + \frac{99}{Q^2}\right)}}{2} = (\omega\tau_o)^2 \qquad (3\text{-}1)$$

Solving for ω yields ω_a and ω_b, the nearest allowable adjacent channel frequencies.

A sample calculation is shown here. Select:

$f_E = 22\ \text{kHz}$

$B_\omega \geq 500\ \text{Hz}$

$Q \leq 20$

$B_\omega(Q\ \text{constrained}) = \frac{22}{20} = 1.1\ \text{kHz}$

$Q^2 = 400, \ \frac{99}{Q^2} = 0.247$

$$(\omega t_o)^2 = \frac{2.247 \pm \sqrt{0.247\,(4.247)}}{2} = 1.1235 \pm \frac{\sqrt{1.05}}{2}$$

$$(\omega t_o)^2 = 1.1235 \pm 0.5125 = 1.636, 0.611$$

$$\omega t_o = 1.28, 0.785$$

$$f_a = 1.28 \times 22 \text{ kHz} = 28.2 \text{ kHz}$$

$$f_b = 0.785 \times 22 \text{ kHz} = 17.3 \text{ kHz}$$

Thus, using equation (3-1), the signaling frequencies were computed to allow for 20 dB of adjacent channel attenuation. The report states that "additional checks must be made as the frequencies are calculated to ensure that the selected frequencies are not harmonically related." Table 3-7 shows the frequencies proposed in the Johns Hopkins/APL report. It was noted in the report that no second or third harmonics fall within 1 kHz of another frequency. It should be brought out at this point that all except one of the selected frequencies were propagated into the final design, even though the functions assigned to the tones in the subject study do not match the final design. Figure 3-3 shows the spectral relationships of the proposed frequency assignments and the final functional assignments. The final MPM system also made use of frequencies above 50 kHz for uplink and downlink FSK communications. It is unclear if any interference analysis was conducted prior to the selection of the FSK frequencies since, as we will show later, they suffered from significant standing waves and harmonic related interference from the low-frequency tones.

Table 3-7. RECOMMENDED COMMUNICATION FREQUENCIES
(Johns Hopkins APL Report)

Tone	Frequency (kHz)	BW (Hz)	Filter Q	Frequency at 20 dB Attenuation (kHz)
CAL	3.75	200	18.75	2.88 — 4.88
A	6.1	500	12.2	4.1 — 9.1
B	10.2	510	20	8.0 — 13.1
C	13.3	665	20	10.4 — 17.0
D	17.2	860	20	13.5 — 22.0
E	22.0	1.1K	20	17.3 — 28.2
F	28.3	1.4K	20	22.2 — 36.2

3.1.3.7 Vital Tone Encoding

Recognizing the criticality of some tones and the need to detect both presence and absence of the tone and validity of the detected tone, the problem of tone encoding was considered. The particular scheme considered in the Johns Hopkins/APL report was all tones transmitted on one loop, whereas the final design has multiple independent loops each carrying, in most cases, only one tone. The discussion, however, is valid in either case. In the proposed scheme, the power amplifier input alternates between sets of vital tones (one or two) at the modulation rate of 50 Hz; in addition, a single unmodulated calibration tone is present continuously in some loops. Calibration was considered to be a nonvital tone and thus required no identifying modulation. Figure 3-4 shows a diagram of this scheme, the intent of which was incorporated into the final multiloop system.

3.1.3.8 Onboard Decoding

The vital tones were to be inductively coupled to the receiver on board the vehicle via the guideway loop and the vehicle antenna. The received signal would be processed and decoded to yield the required commands. Some of the design considerations brought up were the need for an AGC to accommodate for vehicle

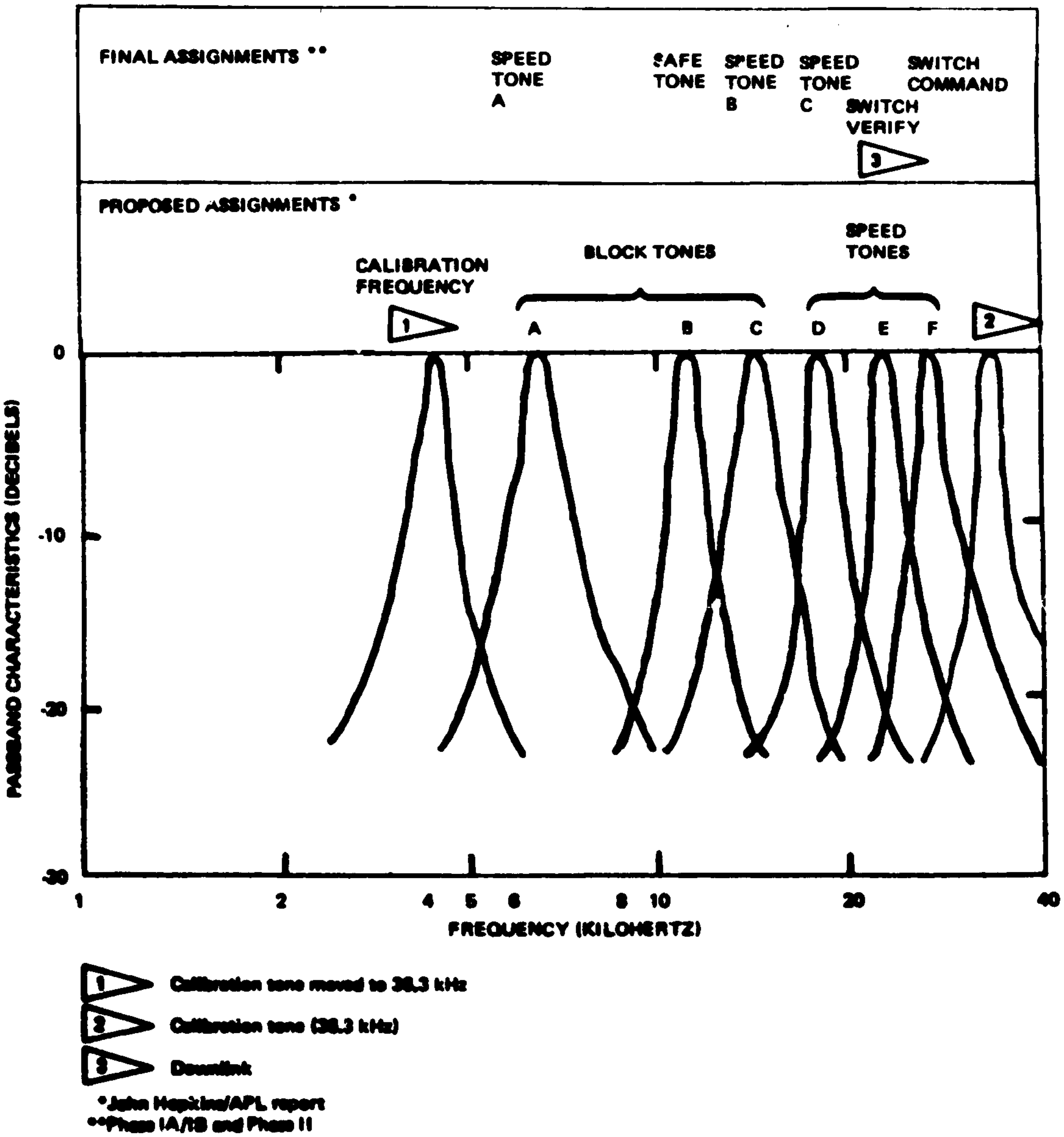


Figure 3-3. Early Frequency Selections and Assignments

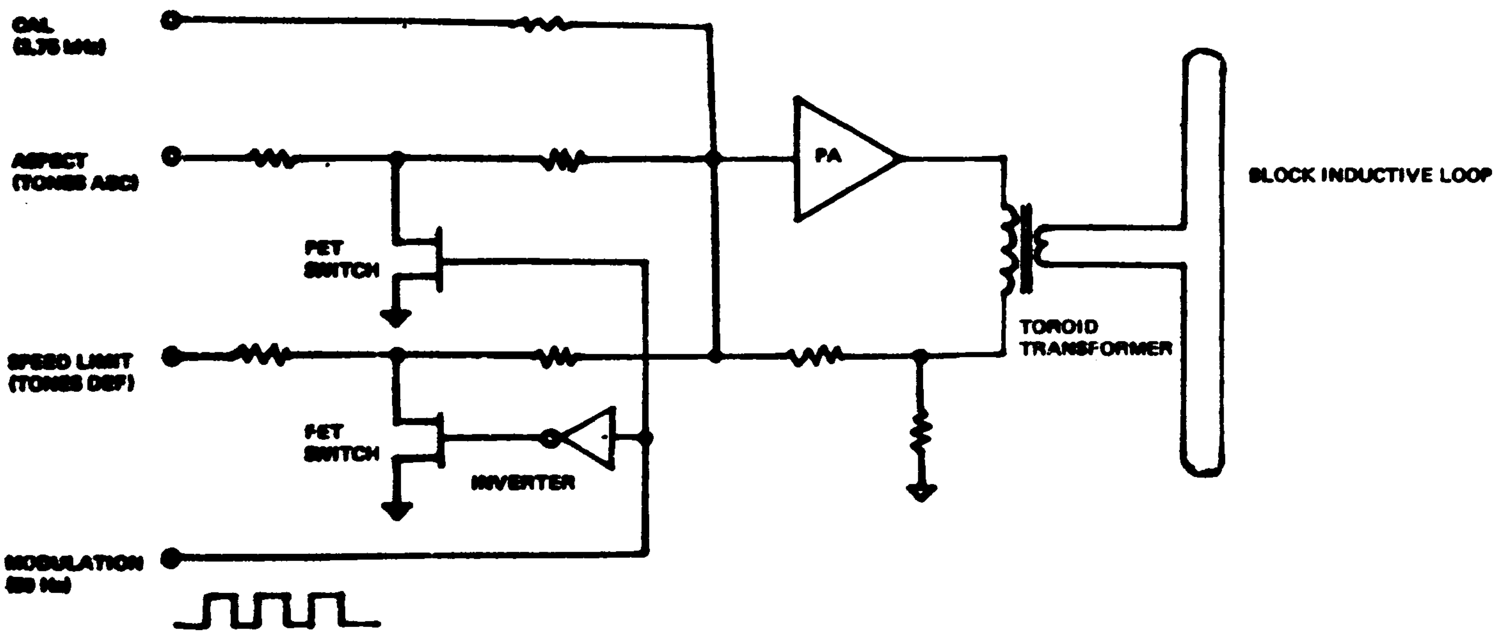


Figure 3-4. Wayside Block Amplifier Circuit (John Hopkins/APL Report)

lateral shift, threshold detectors that contained some hysteresis to prevent noise jitter during switching, and the use of vital relays. Figure 3-5 shows the suggested configuration of the onboard tone decoding.

3.1.3.9 Calibration

Velocity accuracy was to be obtained by transmitting a calibration signal via the inductive communications system over selected portions of the guideway. The vehicle, comparing the known duration of the signal at the commanded speed with the period of time it received the calibration signal, can detect a deviation resulting from its velocity error. This deviation can then be used to generate a velocity correction signal to offset the error. The needed resolution of velocity error was estimated to be 0.25 ft/s.

3.1.4 Summary

Summarizing the recommended design approach to the inductive communication system, as proposed by the Johns Hopkins/APL report, "An inductive communication link is recommended which uses the N-binary encoding format with three tones for speed limits and three tones for block aspect. The ac failsafe coupling technique is provided by switching between these two sets of tones at a 50-Hz modulation rate." The report also recommended the use of either traditional mechanical or newer solid-state "vital relays" to provide certain failsafe features.

The preceding has been a brief but fairly comprehensive discussion of many of the very early conceptual trades and recommended design considerations that were documented. The following sections discuss the design evolution of each subsystem and the problems associated with the particular subsystems through the new phase II design. The evolution will follow the design concept finally selected as presented in section 2. of this document.

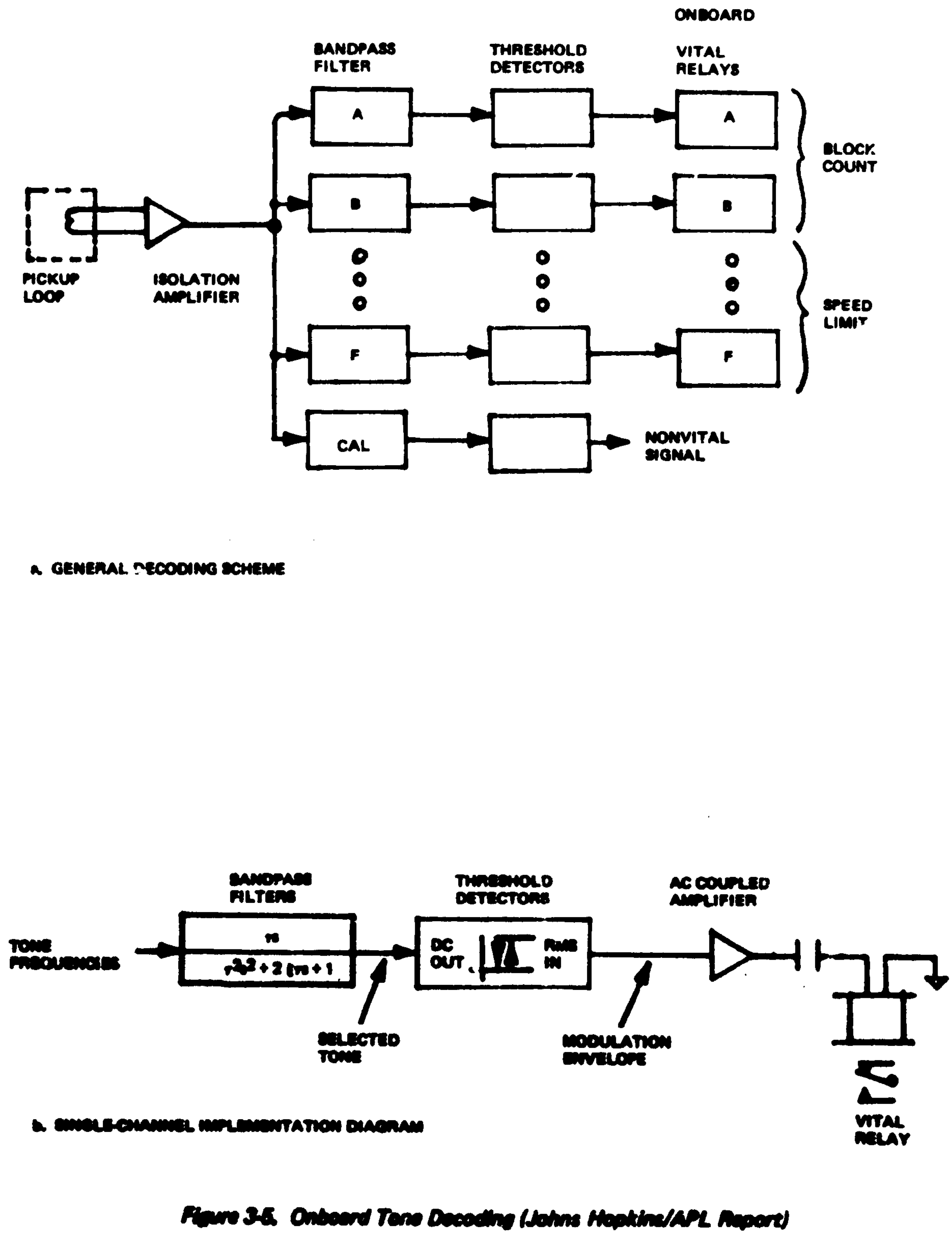


Figure 3-5. Onboard Tone Decoding (Johns Hopkins/APL Report)

3.2 DETAILED DESIGN EVOLUTION

Having completed a review of the conceptual trades leading to the basic Inductive Communication System (ICS), we will discuss the design evolution from that point. Morgantown inductive communications system design can be separated into several major evolutionary steps (fig. 3-6). The first consisted of the early JPL work that resulted in a preliminary system design data package. This package contained the early concepts and appeared, slightly modified, along with Bendix design and conceptual work, as a phase IA system specification in October 1971. Following a Bendix safety hazard analysis (November 1971) and further design work, certain basic changes were made and presented at the phase IA CDR in January 1972. This evolved into a phase IA Communications and Control System (C&CS) specification in March 1972. A program review was conducted by Boeing, the integrating contractor, in January 1973 to resolve phase IB problems that had surfaced. This review and the MPM C&CS safety study (May 1973) further perturbed the phase IA ICS design. The phase IA prototype system testing was completed in September 1973. At the conclusion of this testing certain changes were proposed and incorporated into the phase IB system.

One of the most significant changes was a new VCCS, designed and built by Boeing, guided by specifications derived from a communications system study. The study was to comprise measured data taken on the phase IA guideway during the summer of 1973 and new analysis aimed at deriving a workable communication system model. During the phase IB system test phase further communications problems were uncovered and some minor design changes were made. Most of the problems involved parts reliability, circuit card performance, noise and signal margins, and difficulties with the phase IA loops buried in the guideway. A substantial guideway loop rework and upgrade was undertaken in April 1975. The phase IB system was demonstrated and put into passenger service in September 1975.

Following the decision to expand the system to add more guideway and two more stations, a phase II contract was awarded in November 1976. For phase II portions of the system the ICS was substantially redesigned to improve reliability and reduce system costs. This redesign consisted of adopting a "master oscillator" concept using one set of redundant oscillators as the signal source for all loops within

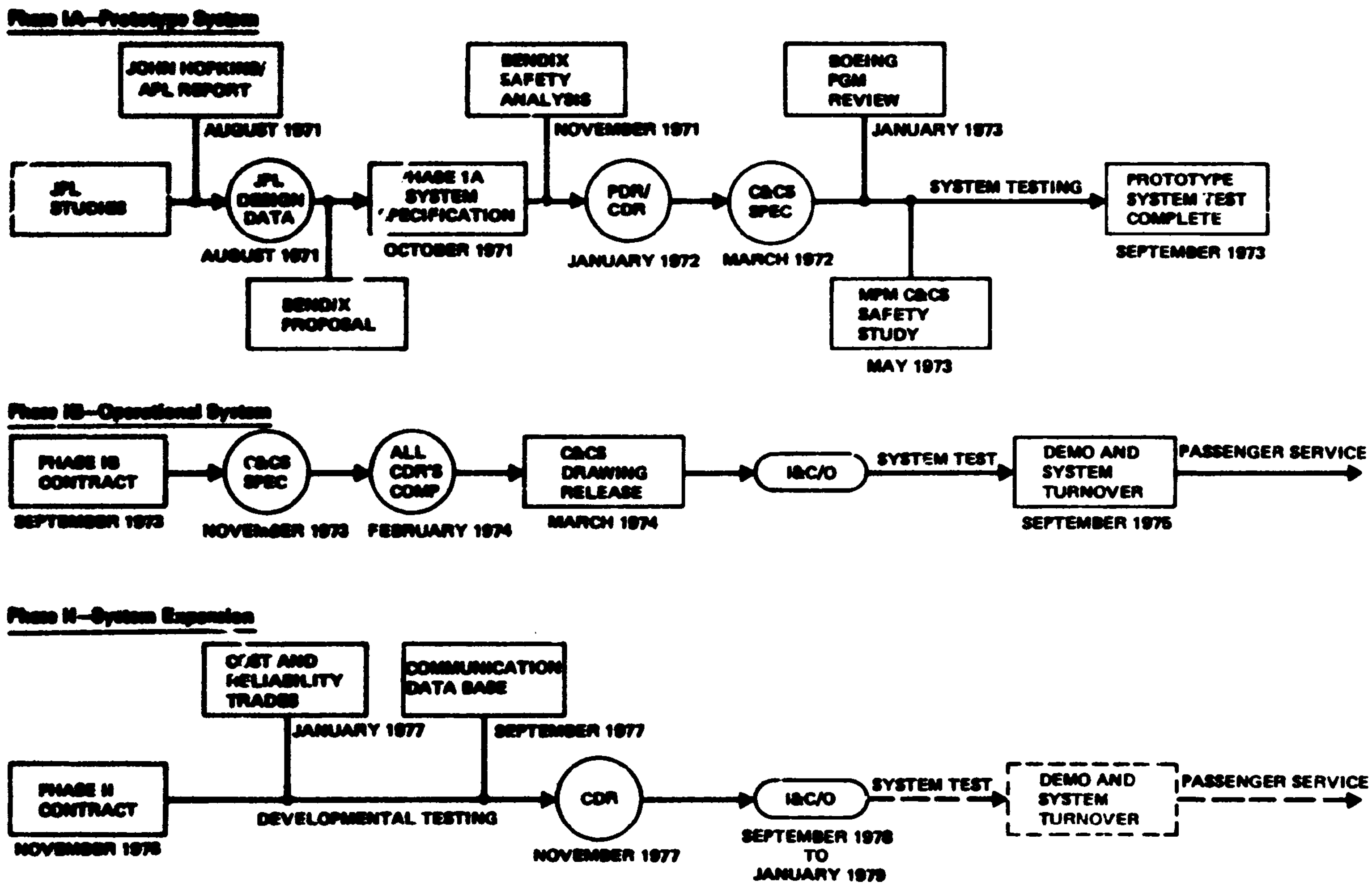


Figure 3-6. System Design Evolution

a station. In addition, switch, stop, and calibrate transmitter cards to control multiple loops were designed. Lastly, the FSK transmitter and loop driver cards were replaced with new designs to obtain more drive current, reduce distortion, eliminate leakage, and improve overall reliability. As a result of these station electronics changes, card count in the new stations was reduced by 30 percent to 40 percent with a similar reduction in parts count. Changes were made to the guideway loop installation methods with the adoption of an innovative loop balancing concept that reduced the total number of crossovers by 20 percent to 30 percent. Changes also were made in the loop installation criteria with the elimination of splices in the guideway, relocation of termination resistors to the cable trays, and the recommendation of a new wire type aimed at a substantial improvement in reliability. A new and more detailed communication analysis and model also was undertaken.

In the following subsections the design of each major subsystem of the inductive communication system is discussed, from its earliest concept through the phase II design. Problems and pitfalls will be discussed to familiarize the reader with those items critical to the successful design and development of an inductive communication system.

3.2.1 C&CS Subsystem

The Inductive Communications System is shown in figure 3-7. It encompasses the uplink transmission and downlink receiving subsystems located in the station electronics, the loops located in the guideway, and the VCCS receiving and transmitting subsystems located in the vehicle.

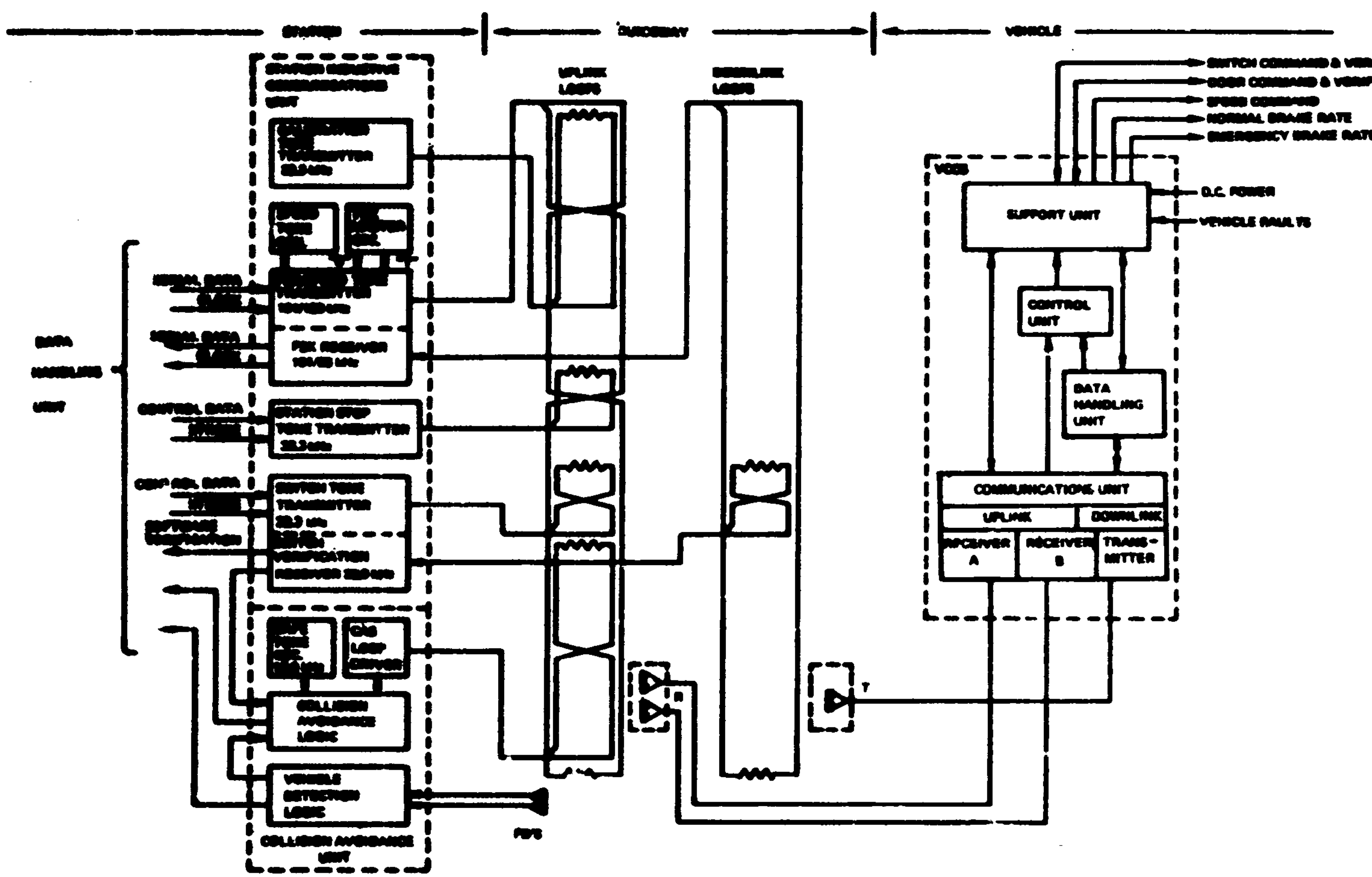


Figure 3-7. Inductive Communications Subsystem (Phase IB)

3.2.1.1 Speed Command and FSK Subsystem

Speed command and related velocity communication requirements were developed as part of JPL's design data package. It was determined that the speed command should be continuous and failsafe, discontinuities must be recognized by the vehicle, and the speed command must never exceed the guideway civil speed limit. The concept developed contained (1) a speed command unit generating the civil speed command from combinations of three discrete tones and (2) a velocity communications unit using a continuous tone and wiggle wires to provide acceleration and deceleration profiles to the vehicle.

Speed Command. The speed tone unit was to utilize three tones chopped 50 percent of the time by a modulating switch that would allow "failsafe" reception on the vehicle. In the early concepts the station computer could select any speed command the same as or less than the guideway civil speed. The tone combinations would command up to six speeds as shown in table 3-8. Preliminary specifications required a nominal loop current of 100 mA rms to achieve a 15-dB signal-to-noise ratio in a vehicle receiver having 20-ms integration. Each speed tone unit would be dedicated to a particular loop and section of guideway.

TABLE 3-8. EARLY SPEED COMMAND FREQUENCIES AND CODING

TONES ▷1			CODED MESSAGE CIVIL/COMMAND SPEED
TONE A (2.4 kHz)	TONE B (3.75 kHz)	TONE C (6.1 kHz)	
1	1	1	44 fps
1	1	0	33 fps
0	1	1	22 fps
1	0	1	9 fps
1	0	0	6 fps
0	1	0	4 fps
0	0	1	0.1 g stop
0	0	0	0.3 g Emergency stop

▷1 All tones 100% modulated by 50 Hz square wave.

The requirement for velocity commands arose from the need to control a vehicle's upspeed and downspeed transistors. It was felt that the problem called for a continuous commanded speed profile or numerous discrete commanded speed steps. Early design data recommended implementation of the wiggle wire as a method of obtaining a continuous command profile.

Using a continuous command profile, the vehicle would receive a civil speed command of the final velocity in addition to a wiggle wire reference profile. The wiggle wire reference would provide a series of nulls with the distance between the nulls being the variable that provides speed profile information. The closer the nulls, the slower the vehicle speed. Tone F (28.3 kHz) was assigned to the ramp profile and reverse command unit. The reverse command would be 50 Hz modulated and detected only if the vehicle commanded speed was less than 4 ft/s. (The vehicle reverse mode was deleted prior to the phase IA specification.) The ramp tone was not modulated except by the phase reversals. Phase reversals were to be spaced so as to center around 4 Hz (a function of reversal spacing and vehicle speed). One ramp generator would power all wiggle wire loops in a station, and failure of the vehicle to receive a ramp tone during a speed transition would result in an emergency brake stop.

By the time the phase IA developmental specification was prepared, the ramp tone generator had been deleted in favor of incorporating a profiler internal to the VCCS that would provide constant acceleration and deceleration at transitions of 2 ft/s^2. Thus, track geometry was required to accommodate a fixed profile. The computer-controlled speed commands were deleted and a fixed civil speed command used. The provision to command normal or emergency stops via the speed command system also was deleted. The tone frequency assignments were revised, and a previously included status monitor (go/no-go) of circuit cards was deleted. Table 3-9 shows the final speed tone assignments developed by Boeing and Bendix. Note that the no-tone or three-tone conditions are illegal civil speeds and the vehicle will default to the lowest speed command of 4 ft/s. The frequency assignments were such that the higher speeds are commanded by the lowest frequency tones, thus precluding to some extent inadvertent higher commands due to harmonics. Also, in a two-tone command, failure of one tone will result in a lower commanded civil speed.

FSK Subsystem. Both uplink and downlink digital data are transmitted via an FSK communication system. In the original concept, the data were to be transmitted in serial format using a three-frequency FSK system. For the uplink system a center frequency of 125 kHz was selected with a frequency shift of ±4 kHz—resulting in frequencies of 129 kHz for the "1" bit and 121 kHz for the "Ø" bit. Note that frequencies selected are considerably above the maximum recommended in the Johns Hopkins study. Data would be transmitted with a 50 percent duty cycle at a bit rate of 1,000 bps. Two 16-bit words were to be sent in each message with the second word being the complement of the first for error-checking purposes. Transmission was asynchronous with nulls (or spaces) between messages to establish message sync. The associated receivers would convert the serial FSK to NRZ digital data, with a derived clock, for transmission to the station or VCCS data handling units. The downlink system was similar to the uplink except a frequency of 100 kHz was used as the center frequency with the ±4-kHz deviation resulting in

TABLE 3-9. FINAL SPEED COMMAND FREQUENCIES AND CODING

TONES [1]			
TONE A (6.1 kHz)	TONE B (13.3 kHz)	TONE C (17.2 kHz)	CODED MESSAGE CIVIL/COMMAND SPEED
1	1	Ø	44 fps
Ø	1	1	33 fps
1	Ø	1	22 fps
1	Ø	Ø	8 fps
Ø	1	Ø	6 fps
Ø	Ø	1	4 fps
Ø	Ø	Ø	4 fps [2] Default
1	1	1	4 fps [2] Default

[1] All tones 100% modulated by 50 Hz square wave.

[2] Illegal Civil Speed - Vehicles default to 4 fps and downlink fault msg.

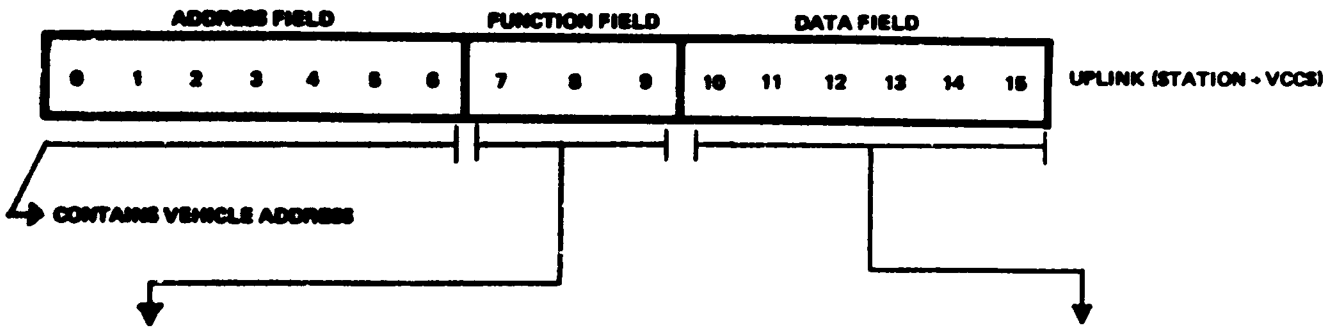
frequencies of 96 kHz for "Ø" bits and 104 kHz for "1" bits. Receiver sensitivity in the VCCS was to be 1.7 mV rms ±20 dB in absence of external noise, and the station receiver sensitivity was 10 mV p-p or greater. The initial goal was a bit error rate of less than 10^{-6}.

The phase IA developmental specification shows a very similar FSK system with the exception of the deletion of the 125- and 100-kHz center frequencies. The exact reason for the center frequency deletion is not documented; however, it can be assumed that since the FSK and speed commands are mixed in the FSK transmitter and share a common loop driver, the extra power required to transmit a continuous center frequency simultaneously with speed tones was unwarranted. The only other changes were in receiver sensitivity and bit error rate; numerous receiver threshold changes were made on the uplink side while the bit error rate was later lowered to 5×10^{-4}. In retrospect, some benefit would have derived from keeping the center frequencies and using them to set an AGC in the VCCS receiver. Some of the later problems would have been eliminated had the receiver threshold been set by such an AGC.

The uplink and downlink message formats have essentially remained the same throughout system development, with the exception of an expansion of downlink fault reporting that will be discussed in the VCCS section. The messages are 34 bits long and consist of a start bit, a 16-bit data word, a 16-bit complement, and a stop bit. Figures 3-8 and 3-9 show the phase IA/IB uplink and downlink message formats. Basically, the messages have bits 0 through 6 as an address field, bits 7 through 9 as a function field, and bits 10 through 15 as a data field.

The development we have related so far led to the phase IA FSK/speed tone subsystem shown in figure 3-10 in functional block diagram form. The subsystem remained unchanged through the phase IB program and up to phase II where a "master oscillator" concept was implemented. However, during the phase IA and IB programs some problems did arise at the subassembly level.

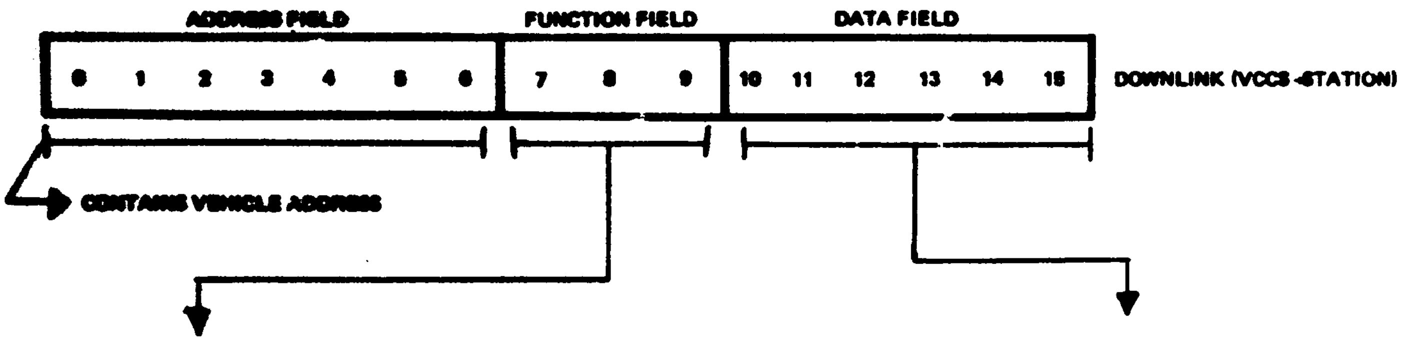
The primary problem that occurred in phase IA was marginal operation in the uplink system. Preliminary analysis yielded loop current requirements of 100 mA rms for all discrete tones (speed, stop, switch, and calibrate) and 33 mA rms for



BITS 7	8	9	CONTENT
0	0	0	EMERGENCY STOP
0	0	1	IDENTITY REQUEST
0	1	0	DOOR COMMANDS
0	1	1	PERFORMANCE LEVEL
1	0	0	UNASSIGNED
1	0	1	RESET EMERGENCY BRAKES
1	1	0	UNASSIGNED
1	1	1	UNASSIGNED

FUNCTION FIELD	BITS 10	11	12	13	14	15
EMERGENCY STOP	X	X	X	X	X	X
RESET EMERGENCY BRAKE	X	X	X	X	X	X
IDENTITY REQUEST	X	X	X	X	X	X
DOOR COMMANDS						
OPEN RIGHT DOOR	0	0	-0	0	1	1
OPEN LEFT DOOR	0	0	0	1	0	1
CLOSE DOORS	0	0	0	1	0	0
PERFORMANCE LEVEL						
0 LEVEL	0	0	0	0	0	0
0.125 LEVEL	0	0	0	0	0	1
0.250 LEVEL	0	0	0	0	1	0
0.500 LEVEL	0	0	0	1	0	0
0.750 LEVEL	0	0	0	1	1	0
0.875 LEVEL	0	0	0	1	1	1
1.000 LEVEL	0	0	1	0	0	0

Figure 3-8. Uplink FSK Message Format (Phase I)



BITS 7	8	9	CONTENT
0	0	0	UNASSIGNED
0	0	1	IDENTITY RESPONSE
0	1	0	DOOR RESPONSES
0	1	1	FAULT REPORT
1	0	0	UNASSIGNED
1	0	1	UNASSIGNED
1	1	0	UNASSIGNED
1	1	1	UNASSIGNED

FUNCTION FIELD	BITS 10	11	12	13	14	15
IDENTITY	X	X	X	X	X	X
DOOR RESPONSES						
RIGHT DOOR OPEN	0	0	0	0	0	1
LEFT DOOR OPEN	0	0	0	0	1	0
DOORS CLOSED	0	0	0	1	0	0
FAULT REPORT ▷1						
EXIT NOT CLOSED	X	X	X	X	X	1
VCCS FAULT	X	X	X	X	1	X
OVERSPEED	X	X	X	1	X	X
LOSS OF SAFE TONE	X	X	1	X	X	X
LOSS OF PRIME POWER	X	1	X	X	X	X
VEHICLE UNDERSPEED OR LOSS OF BRAKE REDUNDANCY	1	X	X	X	X	X

▷1 PHASES IA AND IB ONLY

Figure 3-9. Downlink FSK Message Format (Phase I)

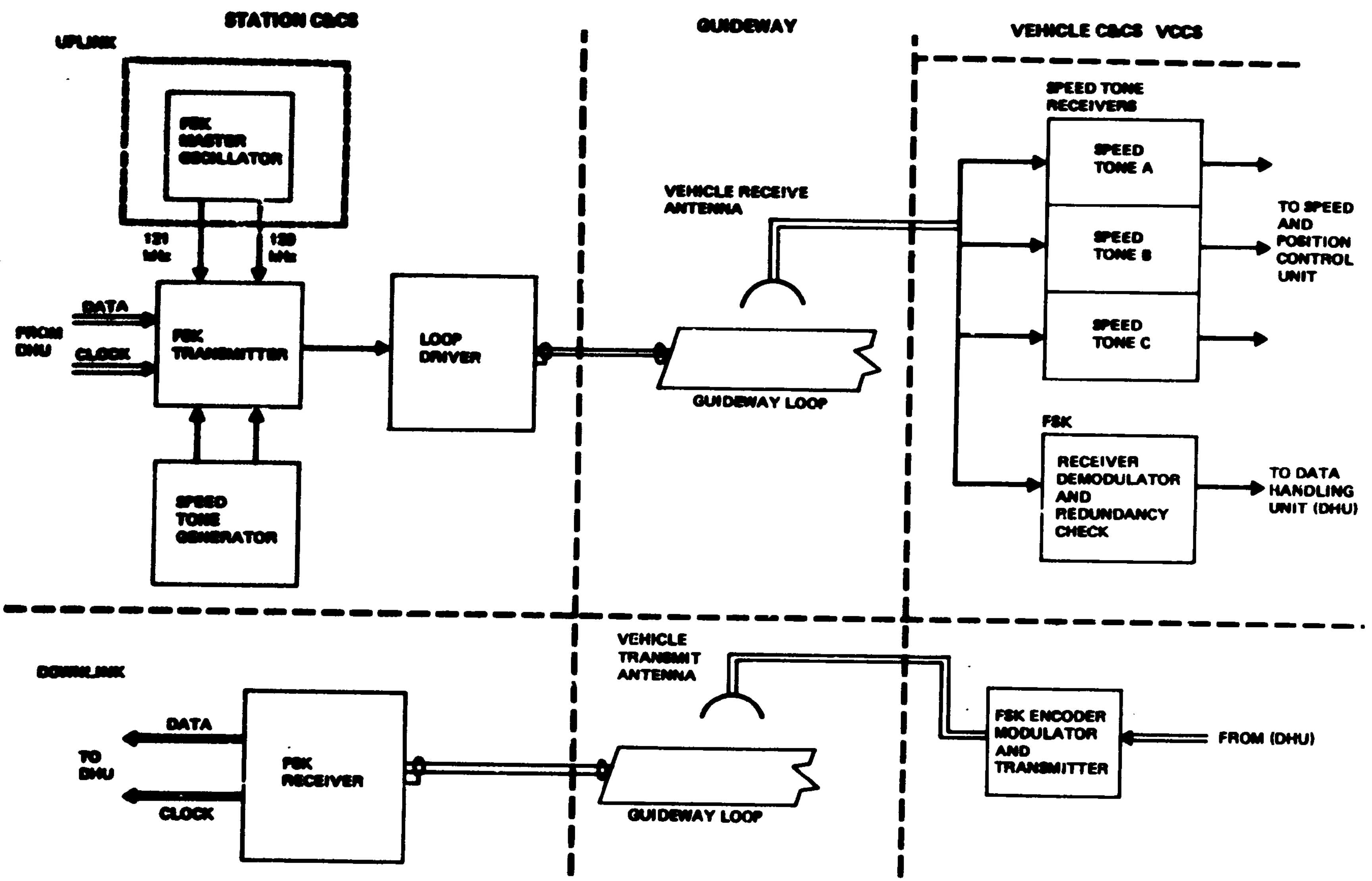


Figure 3-10. Speed Command/FSK Subsystem (Phases IA and IB)

FSK into a loop terminated in 150 ohms. These values were in the phase IA specification, and the loop driver was designed to meet them. The initial loop driver (and FSK transmitter) design provided no means for adjustment. In actuality the current requirements to meet the VCCS receiver sensitivity threshold turned out to be from 250 to 700 mA p-p for discrete tones and 250 to 350 mA p-p for FSK. It is suspected that this disparity resulted from inaccuracy in the original system model, along with problems like antenna tracking errors, loop standing wave (FSK), loop installation errors, and a noisier than expected environment. Early in the phase IA program, adjustments were made to the FSK transmitter and loop driver to allow the gains to be increased to meet the above current requirements. This, however, resulted in excess distortion because the cards were designed for linear operation at much lower levels. The distortion produced harmonics that were detectable in other pass bands, thus causing interference. Two specific examples are (1) the seventh harmonic of 17.2 kHz (120.4 kHz), which caused the VCCS receiver to see a continuous "ϕ" (121 kHz) and either lock up and refuse to accept messages or in some loops just have a high bit error rate, and (2) the sixth harmonic of 6.1 kHz (36.6 kHz), which caused interference with the calibration receiver (36.3 kHz). Another problem, which resulted in part from the modifications to add adjustment capability, was increased leakage of the unmodulated FSK frequencies (121 and 129 kHz), which was amplified by the loop driver and resulted in erratic operation of the FSK receiver in the VCCS. Also, erroneous downlink messages occurred, caused in part by the speed tone receivers seeing three tones for longer than 300 ms at some speed transitions and interpreting them as illegal civil speed. This was related primarily to attempts to run at the lower performance speed levels. It should be noted that the reason higher order harmonics still have considerable effect on the system is the inherent high frequency emphasis in the inductive link. Whereas the transfer impedance at 6.1 kHz might be nearly -32 dB (relative to 1 ohm), the transfer impedance at 121 kHz would be around -3 to -4 dB thus negating the usual rolloff of higher order harmonics.

The phase IB system, as mentioned, has the same functional flow as the phase IA system (fig. 3-10), though changes were made to attempt resolution of some of the phase IA problems. The primary change was a new VCCS designed to meet signal conditions present in the phase IA guideway as determined by a guideway survey and signal mapping. The result was a VCCS with more sensitive receivers intended to resolve some of the margin problems previously encountered. Tests at the Seattle Transportation Test Facility (STTF) using the new VCCS showed that the sensitivity was adequate; however, problems related to leakage and harmonics generated in the station electronics were still present.

The leakage discovered during phase IA precipitated modifications to the FSK transmitter card and shielding of all wires carrying the FSK signals within the drawers. The leakage found in phase IB was localized to the FSK transmitter output stage, and it was determined that no change short of redesign would rectify the problem. As a result, high-frequency rolloff was added to the loop driver and a compensating increase in gain was provided in the FSK transmitter, thus getting a high signal-to-leakage ratio on the guideway.

Insufficient drive from the loop driver and associated high distortion were constant limiting factors in attaining adequate signal margins. An attempt was made to ameliorate the problem with the existing loop driver by increasing the power supply voltage to 60V (along with replacement of low-voltage components); also, the output transistors were changed to a complementary beta-matched pair to reduce distortion and achieve further increase in output. In addition, the loop termination resistor was reduced from 150 ohms to 75 ohms, which analysis showed to be the most efficient resistance for loop driver operation. This change resulted in a tolerable increase in the FSK standing wave, but complicated loop adjustment slightly by making it more critical to check all points in a loop to verify none are out of specification.

Another phase IB problem was recognized as a result of an incident where a switch tone loop was shorted to an FSK loop causing an inadvertent incorrect switch command elsewhere on the guideway. The short was caused by the wires being crushed in an expansion joint located on the elevated portion of the guideway. This type of short represented a potential hazard in the station areas where a 4-ft/s (17.2 kHz) loop and an 8-ft/s (6.1 kHz) loop could short together causing a commanded speed of 22 ft/s, which would exceed the maximum civil speed in that section of the guideway. To eliminate the risk from this type of situation, a high/low speed enable circuit was implemented, controlled by magnets in the guideway. Vehicles, once initialized, would be toggled to high speed (two tones) or low speed (one tone) enable as they enter and exit the station areas. Therefore, if a vehicle were to receive the wrong type of speed tone (e.g., two tones in a low-speed area), it would go to 4 ft/s and downlink a "speed enable" fault. A similar type of fault was postulated that could occur in a high-speed area at certain speed transitions where cancellation of the common tone from two high-speed (two tone) loops might result in an even higher speed being commanded. An example would be the cancellation of 17.2 kHz in a short between a 22-ft/s (6.1 and 17.2 kHz) loop and a 33-ft/s (13.3 and 17.2 kHz) loop to produce an invalid 17.2 kHz. This could occur due to an out-of-phase condition where the 17.2 kHz from each loop occupies alternate time slots, thus removing the 50-Hz modulation and causing the VCCS receiver to determine it to be an invalid tone. Only a valid 6.1 kHz and a valid 13.3 kHz would remain, resulting in a 44-ft/s commanded speed. The problem was eliminated by installing local speed tone synchronization between the adjacent loops such that the 17.2-kHz tone on each loop would always occupy the same time slot. Therefore, in a shorted condition three tones would always be detected by the VCCS, and an illegal civil speed reaction initiated.

By September 1975 all of the problems had been resolved and the system was put into passenger service. Availability rose to nearly 99 percent within the first year. In November 1976, when the phase II contract was awarded, studies were made to determine the cost of replicating the phase IB concept in the new stations. It was found, for the new stations, that equipment and maintenance costs could be reduced and reliability and performance margin increased by redesigning certain elements of the ICS system to take advantage of our experience in phases IA and IB.

The phase II speed command and FSK subsystem (shown in fig. 3-11) incorporates a master oscillator concept for generating the speed tone frequencies. Each station is equipped with a single set of master oscillators, one for each frequency, replacing the hundreds of oscillators on cards previously dedicated to each loop. To ensure high reliability, the master oscillators contain redundant crystal oscillators and automatically switch to a backup upon failure of the primary oscillator. All loop signals within a station are in sync so it's a simple matter of selecting the proper phases and frequencies to create the desired speed command. The FSK transmitters and loop drivers are also new designs.

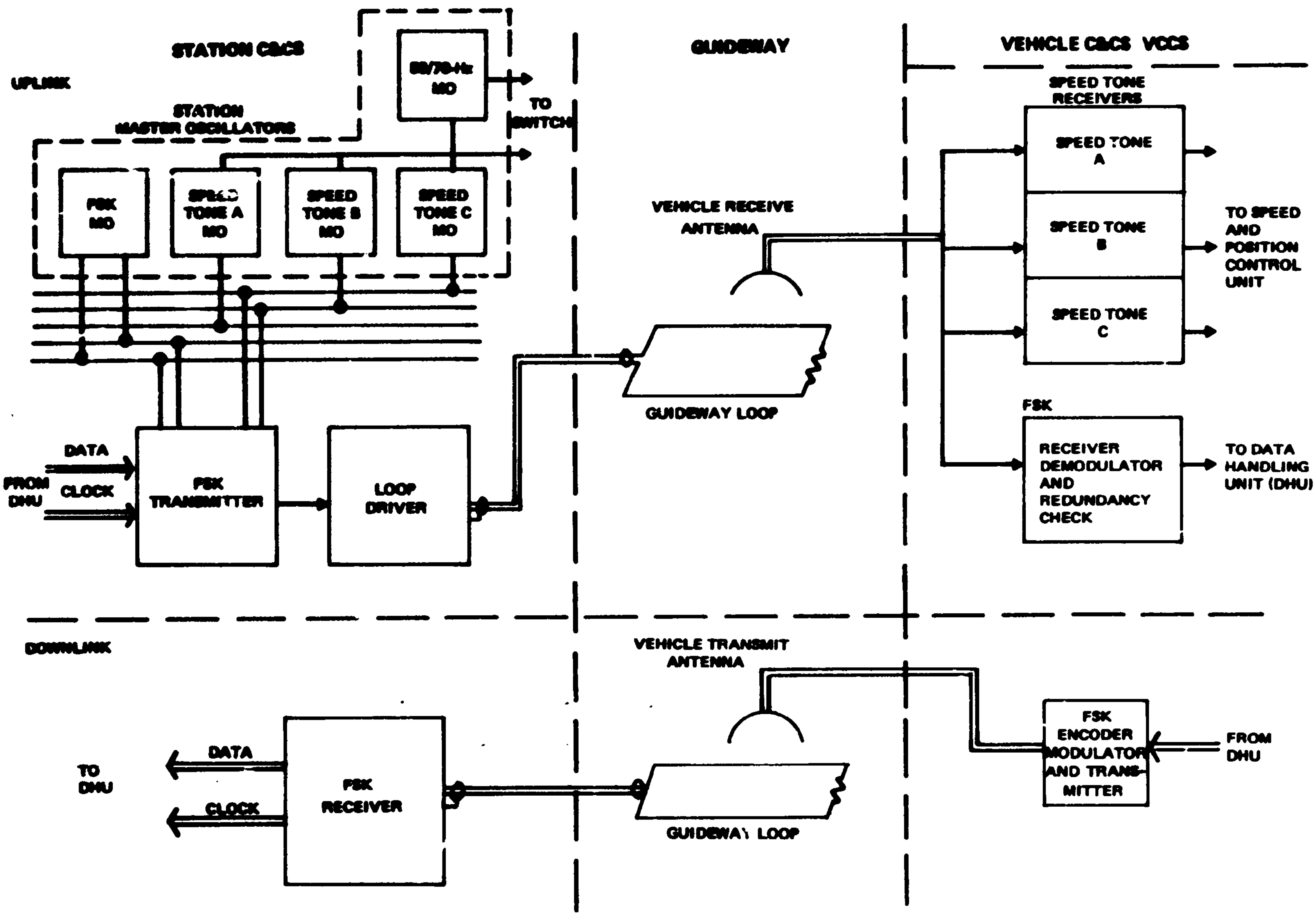


Figure 3-11. Speed Command/FSK Subsystem (Phase II)

The FSK transmitter was redesigned to minimize on-card leakage. The 121- and 129-kHz master oscillator source to the card has been buffered by phase-locked loops to eliminate effects of any coupling prior to the card, and analog switches were used in the modulating portions of the card to increase "on" to "off" isolation. The new loop driver has a hybrid power amplifier that is current limited and incorporates an automatic thermal overtemperatue shutdown feature to protect the unit against shorted loops. The output is transformer coupled to the loop to provide high isolation and maximum power transfer. Overall distortion from master oscillator source, through the FSK transmitter and loop driver and out onto the loop, measures less than 1 percent in most cases, causing negligible harmonic generation. Total power output capability from the loop driver was designed to exceed that required by the worst-case loop in the phase IB system. At this time the phase II system has been fully tested at the STTF and in our system integration laboratory and meets all of its design specifications.

3.2.1.2 Switch Command and Verification

The switch command subsystem consists of an uplink transmitter in the station electronics that transmits a coded signal corresponding to a "switch right" or "switch left" command. Some switches are fixed and are hardwired to transmit only one command while others, at demerges, are computer controlled. The vehicle has an uplink receiver that decodes the command and initiates vehicle switching. Vehicle switching must occur within a certain maximum time interval after which a "switch verification" signal is downlinked by the vehicle. The receiver in the station electronics decodes the switch verification signal and notifies the CAS that switching has been completed, thus allowing the vehicle to proceed. Lack of switch confirmation results in an emergency brake stop by the vehicle due to loss of safe tone in the switch guard loop (CAS).

The requirement for switch commands comes from the method of vehicle steering control. A switch command must be sent to a vehicle at each merge and demerge point on the guideway. This command identifies the side of the guideway to be used for steering reference. At a demerge this controls the direction a vehicle takes, and following a merge it informs the vehicle which side of the guideway has steering rail and power. (In phases IA and IB vehicles, both power collection and steering are switched; in phase II, power collection is a "run-on/run-off" type and only steering is switched.) Each switch must be protected such that when a command and a verification of switching by the vehicle is not received, the collision avoidance system will bring the vehicle to a safe stop.

The earliest concept used an uplink transmit frequency of 17.2 kHz and a downlink frequency of 22 kHz, with 50-Hz modulation indicating a right switch and 70 Hz, a left. Receiver sensitivity was to be 1.7 mV rms with 50-ms integration, and switching was to be completed within 2 sec of reception. The phase IA specification changed the uplink frequency to 28.3 kHz, assigned a performance design goal of 20 dB signal-to-noise ratio, and determined that the loop length should be such that the vehicle will be in it at least 1.5 sec. A "go/no-go" status logic originally proposed was also deleted. The communication to the phase IA CAS was a continuous 25-Hz a.c. square wave if verification had been received. Output drive to the loop was to be 200 mA p-p.

Two significant problems cropped up in phase IA system testing. The first was that inadvertent switching occurred at places other than in switch loops. Documentation is sketchy as to the source of these inadvertent commands but, although unsupported by measured data, it can be speculated that they were caused by detection of the second harmonic of a 13.3-kHz speed tone (26.6 kHz, 50-Hz modulation) as a switch right. Data taken of guideway spurious signal levels during phase IB tend to support this conclusion. In the phase IB system the possibility of inadvertent switches at other than switch loops was eliminated by adding a switch enable system. This extremely simple system proved quite effective. A magnet was buried in the guideway at the beginning of each switch loop, and a reed switch was added to the vehicle, located to pass over the magnet in a properly tracking vehicle. Activation of the dual redundant reed switches by the magnet enabled the switching system in the VCCS to permit reception of a switch command for a period of 375 ms. At all other times switch commands were ignored.

The second problem was reception of false switch verification signals in the station during vehicle acceleration and when track power was cycled. As a result of this problem the phase IA switch verification receiver underwent several modifications aimed at reducing common mode sensitivity. The output stage of the switch receiver underwent changes for phase IB to conform to the new CAS design. The 25-Hz square wave was no longer provided to the CAS; instead, the card provided a series of pulses derived from the switch verification modulation that were routed to software and hardware portions of the CAS. Reception of six pulses within a prescribed length of time was interpreted as verification.

Phase IB system testing revealed noise levels on the guideway in excess of expectations. In particular, noise was present in switch loops during switching. When the vehicle had both power collectors out and was receiving power from both sides of the guideway, a significant current unbalance existed that coupled noise into the vehicle antenna. The result was frequent loss of switch command or the delay of its detection to a point where the vehicle was stopped by the CAS for failure to verify. The problem was corrected by several threshold and sensitivity changes to the VCCS, twisting and shielding of the power collector wire bundle, and, most important, addition of the bifilar antenna, which will be discussed later.

During phase IB system testing one failure to switch occurred due to the shorted loops discussed in section 3.2.1.1. In this incident, a "switch right" loop shorted to a long FSK loop causing sufficient switch tone current in the FSK loop to permit detection at the other end of the loop. This problem caused two switch commands to be presented simultaneously to the VCCS; it chose one (the wrong one) and verified switching state, permitting the vehicle to proceed through the CAS guard loop in the wrong state and eventually run out of steering rail. This problem could have been avoided if the station receiver was capable of determining "correct" verification. The receiver presently does not know which direction is the correct direction and therefore verifies for either direction. Following the incident, modifications were made to the guideway and the steering and power rails to eliminate this problem. These are discussed further in section 3.2.2.

The phase IA/IB switch command and verification system is shown in figure 3-12. Figure 3-13 shows the phase II system. In phase II the master oscillator concept was applied to the switch subsystem, resulting in one signal (28.3 kHz) source per station. The transmitter circuitry has been redesigned and condensed so that one card is capable of controlling four loops. Each section of the card can be strapped as a fixed right or left switch or a computer-controlled switch, thus eliminating the

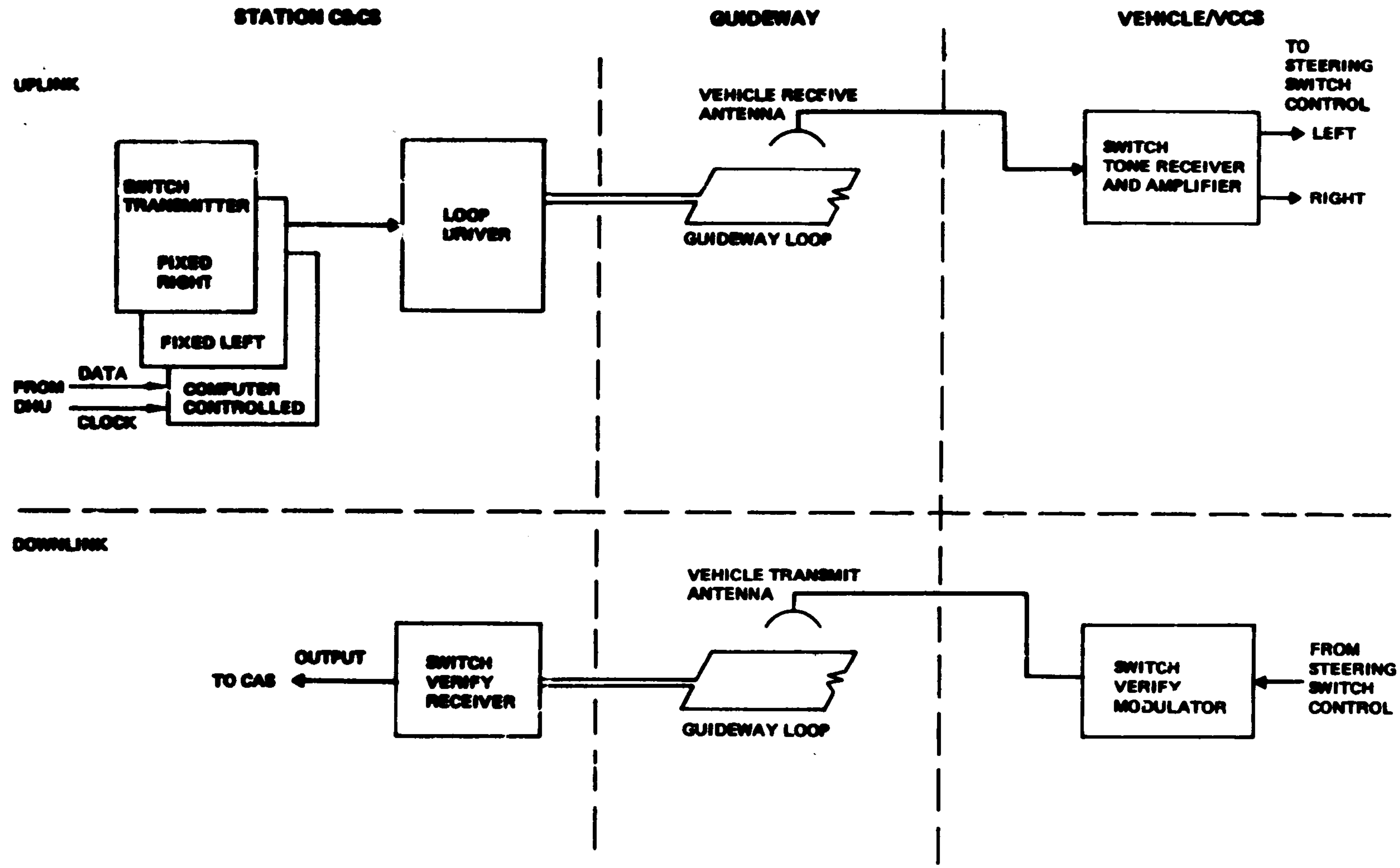


Figure 3-12. Switch Command and Verification Subsystem (Phases IA and IB)

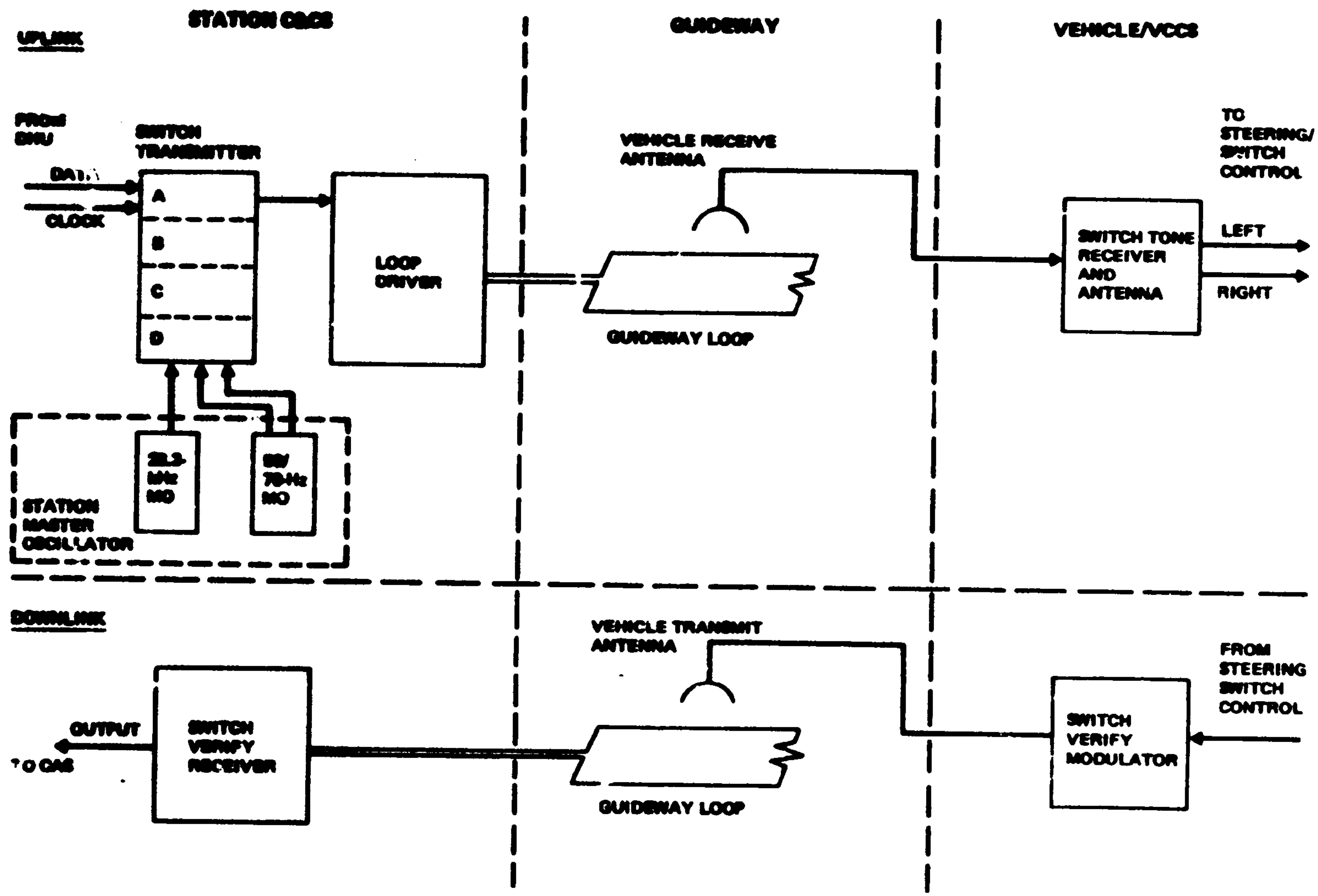


Figure 3-13. Switch Command and Verification Subsystem (Phase II)

three individual card designs previously used. The modulation is received from the 50/70-Hz square wave master oscillator that also powers the speed tones.

3.2.1.3 Station Stop Subsystem

The station stopping subsystem consists of an uplink transmitter located in the station electronics, driving an inductive communication buried loop on the guideway. The buried loop is located precisely in relation to the center of the associated stopping berth such that a vehicle can judge its position relative to the berth to begin a stopping profile. The VCCS contains a station stop tone receiver capable of detecting the discrete stop tone.

JPL and Bendix both did considerable analysis aimed at developing an accurate stopping system. The "open loop" system proposed (in the design data) for phase IA used a prepositioned null in the stop loop to accurately stop the vehicle in relation to the berth. The loop was in the form of a figure 8, thereby causing a null in the center. The null width would be measured using odometer pulses and this distance divided in half to obtain the exact center of the null (assumes no hysteresis in receiver thresholds). The position measurement was to be accurate within ± 1.5 in. to allow stopping error of ± 4.5 in. The stopping had two speed profiles; the first was deceleration after entry of the loop to 1 ft/s at 2 ft/s^2, and the second was braking to a final stop after sensing the null.

The phase IA system specification contained the above stopping concept with some minor revisions. The loop was a figure 8 pattern, with the vehicle decelerating from 4 to 1 ft/s after entering the loop and finally coming to a stop after passing the loop crossover at the center. Overall stopping accuracy was to be ± 6 in. Figure 3-14 shows a sketch of this concept. The stop tone transmitter operated at a frequency of 36.3 kHz (unmodulated) providing a signal level of 100 mA rms into the loop. Two control lines, one data and one strobe, from the DHU toggled the loops on and off. The receiver sensitivity was to be such that signals 20 dB below nominal were not to be detected. The original proposal also had status monitoring, which was deleted in the phase IA specification.

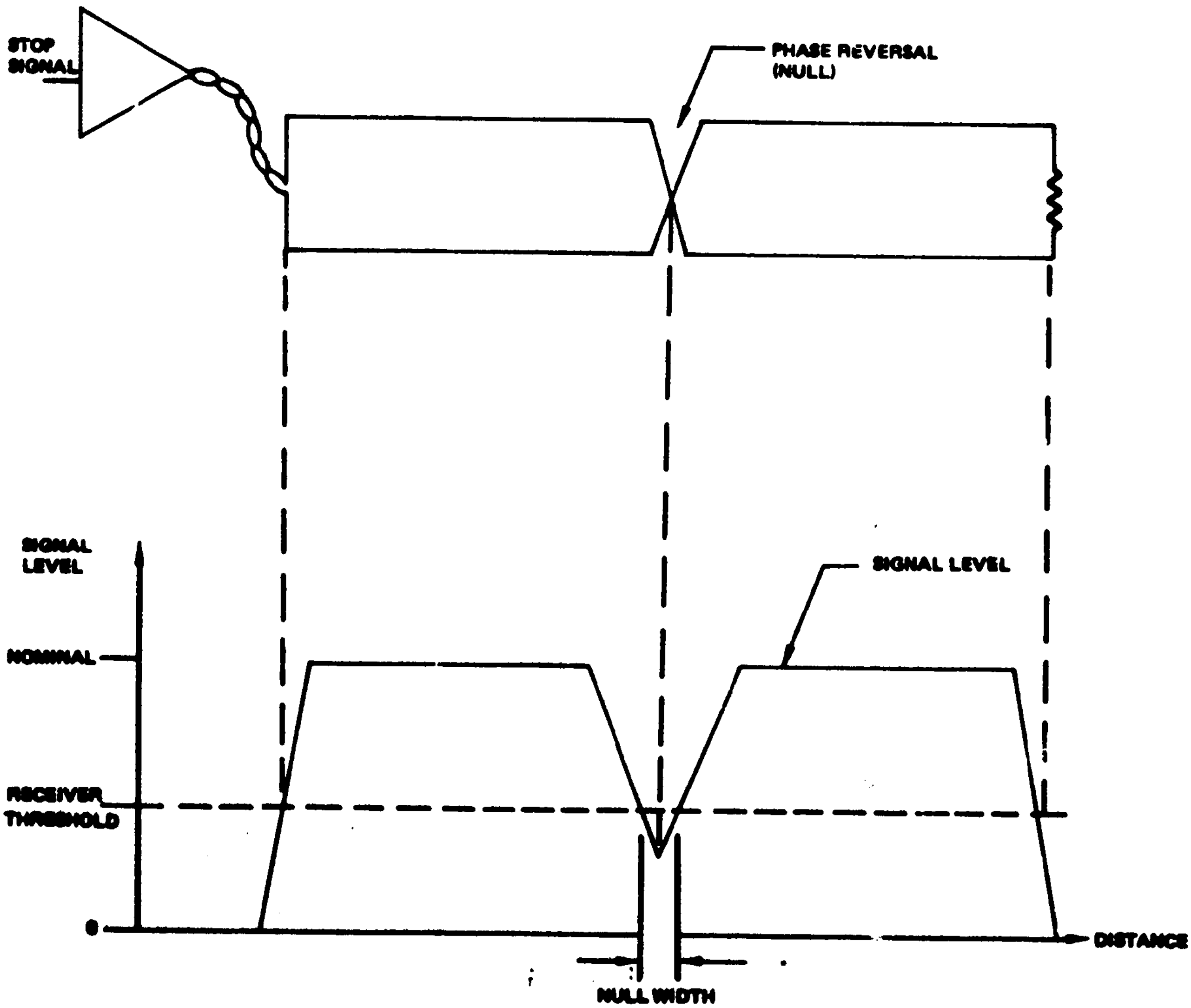


Figure 3-14. Station Stop Loop (Phase IA)

The primary station stop problem in phase IA was related to stopping accuracy. It was found that vehicle velocity control performance during stop sequence was inconsistent, and the ±6-in. (3 σ) stopping position requirement was not being met. The stopping position problems were interrelated with receiver noise sensitivity, gain, vehicle performance, and signal detection thresholds. In phase IA the receiver gain profiles were changed and some filtering was added for noise immunity; however, the fundamental communications problem appeared to be related to (1) accurately detecting the null with some repeatability, vehicle to vehicle and receiver to receiver, and (2) the "open loop" control concept being used.

In phase IB, along with the new VCCS receiver and vehicle modifications, the guideway was changed by eliminating the null (figure 8 loop). Also, the station stop was changed to a "closed loop" system with a single-step profile as a function of position. The phase IB stop profile began at and was measured from the point of first stop tone detection. The VCCS receiver detection threshold was within the range of 2.6 to 9.1 mV p-p, which gave a calculated uncertainty of ±0.78 in. using the rectangular antenna. Since the new stop profile measured distance based on odometer pulses, the largest contributor to stopping error was calibrate loop length errors. This was primarily due to calibrate loop lengths not being corrected for curvature and grade. Position uncertainty was created by some additional errors associated with stop loop installation and by the loop detection tolerance, a function of signal level and receiver thresholds. It also should be noted that changing to the bifilar antenna later in the program introduced an across-the-board error due to the different loop versus antenna "end" effects.

The phase IB system had a different set of problems related to the stop subsystem; noise and signal loss were the major concerns. The phase IB system was not that much noisier than the phase IA system. It appears that many of the noise problems existed in phase IA but were masked by the more fundamental problems already discussed. The fourth rail safety ground, used in station areas to ground vehicle chassis, was responsible for an estimated 12- to 20-dB increase in the noise level in the 36-kHz region, probably due to division of motor currents between the "B" phase of the power collector bundle and the safety ground wire. The noise was of sufficient amplitude to cause false triggering of the VCCS station stop receiver channels or loss of stop tone once it was acquired. Noise in the 36.3-kHz region was also found on dispatch, causing re-entry into the station stop profile. Also, an inadvertent stop tone dropout was occurring when track power was applied, causing a premature movement of the vehicle.

Early in the problem investigation, the effects of increasing the transmitted signal level to achieve a greater signal-to-noise ratio were evaluated. It was found that the relative transmit level had a significant effect on final stopping position because it caused earlier or later stop tone acquisition. Receiver thresholds were changed, which provided some noise margin. A 4-in. discriminator was added, requiring the continuous presence of stop tone for 4 in. of vehicle travel (as measured by the odometer) before a stop tone was recognized. Also, vehicle wiring was rerouted.

About this time another problem emerged: Stop tone dropouts while the vehicle was stationary were detected. The dropouts occurred for a fraction of a second, and it is believed they were caused by momentary dropouts of the crystal oscillator in the stop tone transmitter. The crystal oscillators exhibited a high failure rate and probably became intermittent prior to failure. The effect of a dropout on a vehicle in a station berth was somewhat startling. The vehicle would see a momentary loss of stop tone and begin to dispatch. The tone, however, would be reacquired immediately but due to the 4-in. discriminator the vehicle still would need to move 4 in. before it again could come to a stop. This caused the vehicle to move several inches. Solution to the dropout problem was two-fold. First, the software was modified to assign a 0 percent performance level to vehicles stopped in a berth; a 100% performance level would be assigned just prior to tone removal for dispatch. Second, a timer was added to the 4-in. discriminator so that if a stop tone returned for a period of time the VCCS would again recognize it and reinitialize the stop profilers, thus preventing a 4-in. "lurch" when 100 percent performance level was assigned prior to dispatch.

The final improvement to the stop tone subsystem was the addition of the bifilar antenna, which decreased the received noise level that had caused the original problem. Tests conducted during phase IB integration and checkout revealed that the bifilar antenna had significantly improved the stop tone signal margin to the point where no problems were observed even with station signal levels reduced to minimum. The primary lesson learned was to avoid using "absence" of a tone to command anything except a vehicle fault response.

The phase IA/IB stop tone subsystem just discussed is shown in figure 3-15. In the phase II design, the primary station electronics emphasis was on improved reliability and a reduction of system costs. To this end, the problems of oscillator reliability were addressed and a new vendor was found who would provide crystal oscillators with high-reliability MIL-STD-883-B parts burned-in and tested to specification (previous oscillators were commercial grade). In addition, the individual loop transmitter cards containing one oscillator per loop were deleted and the master oscillator concept was adopted. The station master oscillator contains redundant crystal oscillators with fault-detection circuitry that initiates a switch to the backup unit upon dropout or failure of the primary unit. Fault monitoring and annotation circuits are included on both the primary and backup oscillators. The phase II transmitter cards are capable of servicing six loops per card, and, since calibration and stop tone signals are identical (except for computer control of the tone in the stop loops), the functions were combined on a single card. Calibration loops are permanently strapped on, while the stop loops are connected to the DHU for control. The figure 3-16 shows the phase II station stop subsystem.

3.2.1.4 Calibration Subsystem

The calibration subsystem consists of an uplink transmitter sending a discrete tone, via inductive loops of fixed length located periodically on the guideway, to receivers in the VCCS. By counting the number of odometer pulses occurring as the vehicle passes over a loop with a calibration tone and knowing the exact length of the loop, a vehicle can develop an odometer correction factor to account for tire wear, etc.

Early design studies defined the need for a position feedback to compare with a position reference in order to evaluate vehicle position (and speed) error. Vehicle servos would then act to reduce the error. It was determined that the granularity of position feedback required in the Morgantown system was of sufficient fineness to require an onboard odometer. Odometer calibration then would be required to

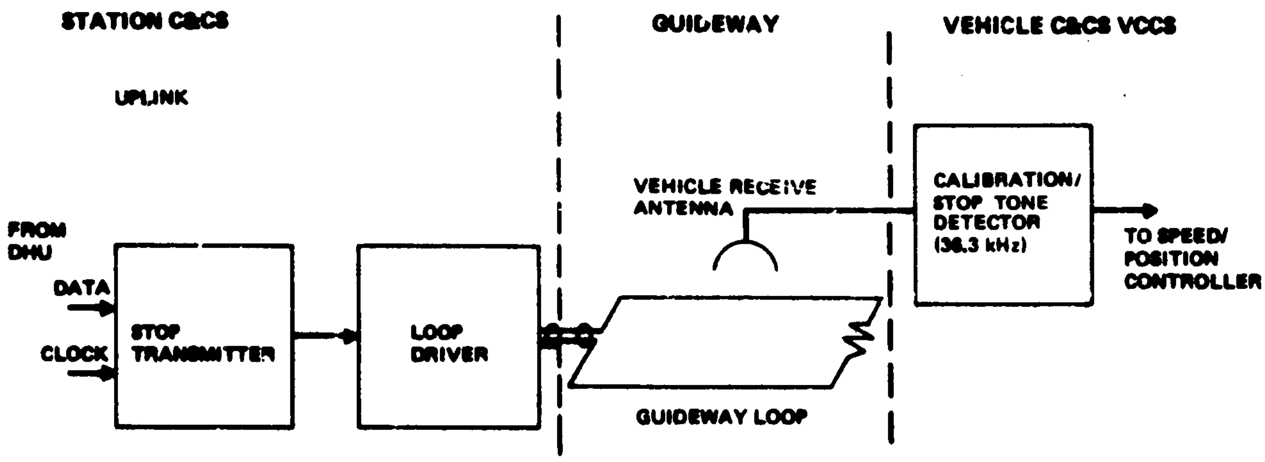


Figure 3-15. Station Stop Subsystem (Phases IA and IB)

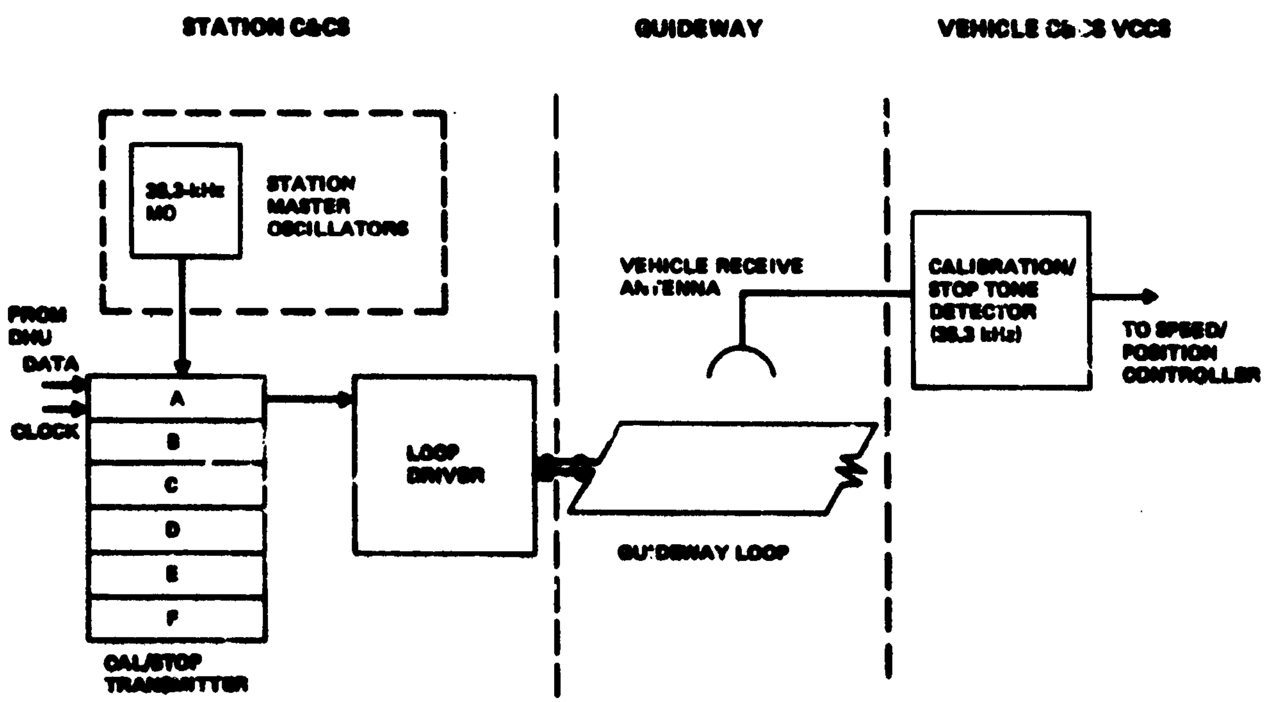


Figure 3-16. Station Stop Subsystem (Phase II)

maintain accuracy since the effective tire radius will vary with temperature, weight, tire wear, and inflation pressure. The following methods could provide adequate distance intervals for calibration through references obtained from the guideway at discrete intervals:

a. Inductive loop and tone signals
b. Magnetic sensing
c. Frequency shifted oscillator
d. Photo cell detectors and light sources
e. Mechanical trips
f. Radio isotope detectors.

Each of the methods considered would provide an accurate distance-traveled measurement to the vehicle since each method could supply a start and end point. The various methods were evaluated, and the inductive method was selected because it was compatible with the other communication concepts.

One long loop or two short loops (start and end) were considered for the inductive method. The single long loop was favored due to savings in hardware. The detection threshold was recognized as a contributor to accuracy for acquisition and loss of the signal. It was assumed that these errors would be self-cancelling. A 200-ft loop length was selected, with loops located at 1000-ft intervals. This was later changed to allow 800-ft intervals or even multiples of 100 ft.

The phase IA calibration tone transmitter was to operate at 36.3-kHz with 50-Hz modulation. Modulation was discarded in phase IB as it contributed to acquisition and loss errors. The output of the loop driver was to be 100 mA rms to provide 15-dB signal-to-noise ratio into a receiver with 20-ms integration. In this subsystem, as with the rest, a logic status check was proposed and later deleted. The calibration and stop tones of the same frequency would be distinguished by comparison with the civil speed command. If the vehicle was going 4 ft/s or less, the tone would initiate a station stop; if greater than 4 ft/s, it would be interpreted as a calibration tone. This worked quite satisfactorily though it produced an interesting anomaly whereby a vehicle that had defaulted to 4 ft/s due to illegal civil speed or some other internal fault would do a station stop at the first calibration loop it encountered.

The only problems associated directly with this subsystem were related to inaccurate layout of the calibration loops on the guideway in certain areas. This was because the radius of curvature used to lay out the loops did not account for loop offset from guideway centerline, thus resulting in length errors for loops on curves. These errors and some other minor location errors were corrected in phase IB.

The phase IB calibration subsystem is shown in figure 3-17. The phase II design modified the system by adding a master oscillator to provide calibration tone (and stop tone) and creating a single multiloop transmitter card for both stop and calibration, as discussed in the preceding section. Figure 3-18 shows the phase II calibration subsystem.

3.2.1.5 Safe Tone Subsystem (Part of CAS)

The safe tone subsystem is an integral part of the MPM Collision Avoidance System. It consists of an uplink transmitter driving CAS loops ranging in length from 20 to 200 ft. The guideway has been divided into blocks of a length proportional to civil speed and vehicle stopping distance. Each block is controlled by one safe tone loop that stretches its entire length. The safe tone, a "safe to proceed" tone, is received by redundant receivers in the VCCS. Loss of the safe tone for longer than 150 ms results in an emergency brake stop by the vehicle.

The original requirements were for a check-in/checkout type of CAS. A "safe to proceed" signal was needed for this. The logic elements had to be made failsafe. Use of solid-state logic rather than vital relays was considered in an effort to minimize space occupied by the equipment. The early system had the speed tones performing the dual function of speed and safe tone by commanding an emergency brake stop with tone removal. The goal was to provide a system with 20-dB signal-to-noise ratio using a receiver with 50-ms integration. One later version of the concept used two frequencies for safe tone; 10.2 kHz was "safe to proceed" in the forward direction, and 13.3 kHz was "safe to proceed" in the reverse direction. Each tone was 100 percent modulated by a 50-Hz square wave. Self-test features also were included.

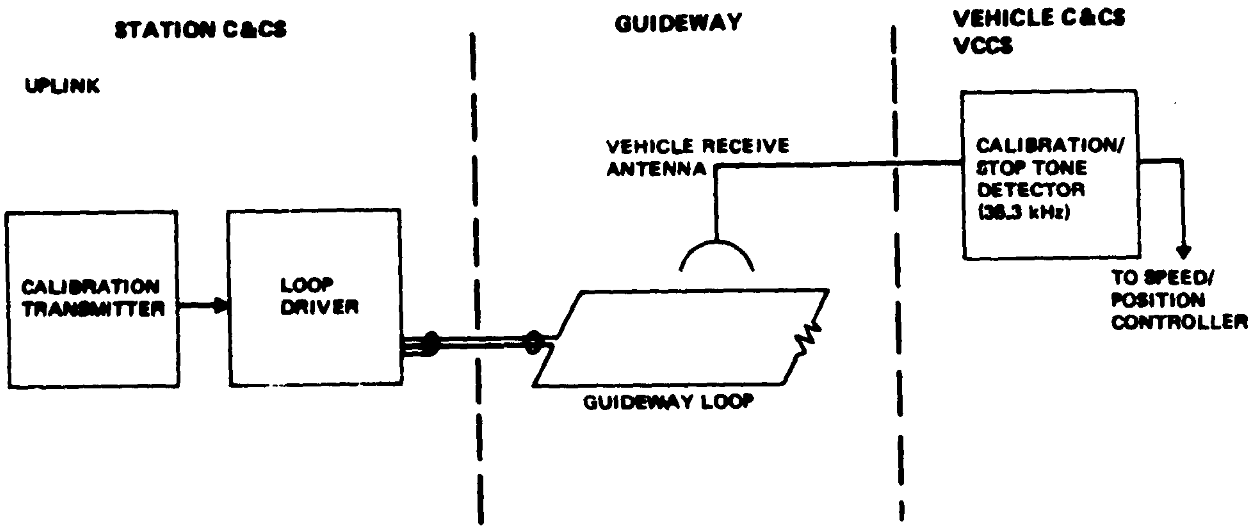


Figure 3-17. Calibration Subsystem (Phase IA/IB)

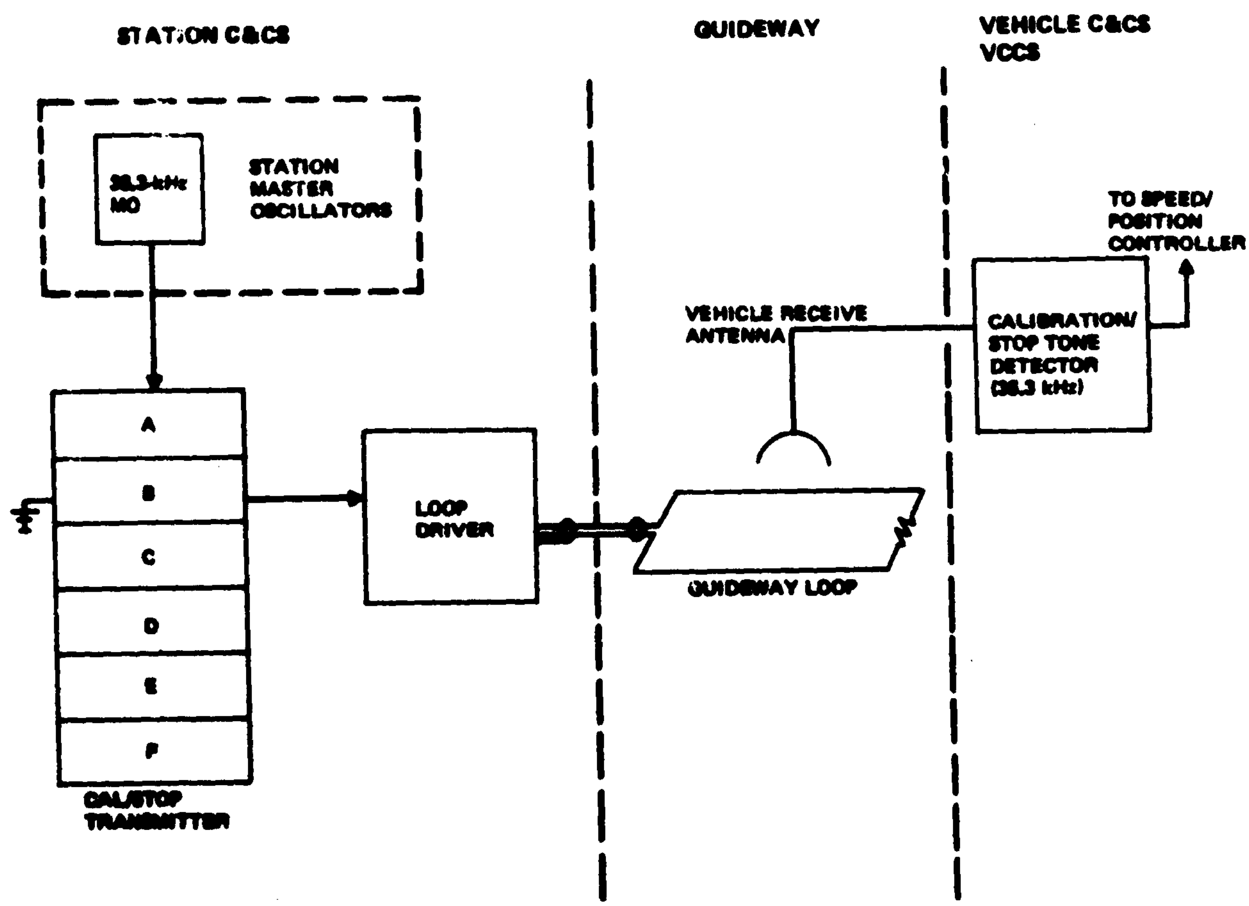


Figure 3-18. Calibration Subsystem (Phase II)

The phase IA system specification describes a system consisting of only one tone (10.2 kHz, 50-Hz modulated) with the transmitter providing an output level that will ensure a minimum signal-to-noise ratio design goal of 20 dB with 50-ms integration measured at the vehicleborne receiver input. This is based on noise environments of MIL-STD-462 and NBS circular 461A when the vehicleborne receiving loop is over the guideway tone loop. Self-test features were deleted. One of the ancillary requirements not specifically mentioned was to ensure that the residual safe tone in an "off" loop remains well below the receiver detection threshold.

The full extent of safe tone problems in phase IA is somewhat unclear; however, numerous tone dropout problems did exist. In particular, it was found that certain crossover spacings necessitated by the loop-to-loop balancing criteria resulted in crossovers under each section of the dual receive antenna at the same instant, causing loss of safe tone in both receivers and a resulting emergency brake stop. Normally, crossovers or dropouts due to loop ends should not affect operation because one receiver should always receive safe tone due to the antenna offsets. Also, to avoid loop boundary problems all loops in a given station were in sync. There is a 10.2-kHz master oscillator for carrier and a 50-Hz master oscillator to supply modulation. Therefore, in theory, a "handover" problem should have existed at the boundary between two stations, though records do not indicate a phase IA problem in this area, probably due to the forgiving nature of the phase IA VCCS design. A recognized signal margin problem did exist, however, due in part to vehicle antenna tracking anomalies and in part to the low level of transmitted signal on the loops. Some investigation was made into methods to increase the phase IA CAS loop driver output (such as reducing termination resistors to 40 ohms (from 60 ohms) and increasing the voltage to the output stage); however, none of these fixes were adopted.

For phase IB numerous changes were made in the CAS system, some of which were a complete redesign of CAS logic, modification of guideway loops (blocks) to go from a 7.5- to a 15-sec headway in certain areas, and, as previously mentioned, the design of a new VCCS. The guideway signal study done prior to phase IB design indicated that the phase IA system had a very small positive margin on the safe tone. Levels 6 dB below the target were measured. As a result of the marginal situation, the new VCCS was made more sensitive in an attempt to recoup some of the lost margin.

One of the very first problems encountered in phase IB was the loss of safe tone at station handover points due to the modulation (50 Hz) of the two stations being out of sync. The out-of-sync modulation caused a ringdown of the VCCS active filter and subsequent loss of safe tone and activation of vehicle braking. The problem was rectified by adding a 50 Hz master oscillator at the central control facility and providing synchronization to slave oscillator cards in all of the other stations.

Another area of concern to all phase IB communication systems was noise, and the safe tone system was no exception. Noise at the safe tone frequencies was found at switches and on the station safety ground. Vehicle-generated noise also was thought to be a problem. Several solutions were implemented to reduce noise in the 10.2-kHz bandpass. One solution was the implementation of the bifilar antenna to reduce noise coupling from the vehicle power and ground wiring. Noise from the station ground (fourth rail safety ground) was further reduced by inserting a 10.2-kHz notch filter in the fourth rail safety ground within the vehicle. Other contributors to the problem were (1) insufficient signal on the guideway and (2) wide variability in receiver thresholds. Therefore, the VCCS sensitivity was modified, in part by hand selecting the phase lock loops used in the receiver, such that the total vehicle-to-vehicle variation was reduced.

As previously mentioned, residual safe tone in "off" loops is also of concern because it could prevent a vehicle from stopping if it were detected by the VCCS. Surveys were made, and some areas were found to be high. The out-of-tolerance loops were caused by improper installation (crossovers out of position, etc.) or by problems related to station wire shield grounding. As a result, the grounding scheme at that station was reworked, and all loop feed cable shields were tied directly to the station ground at the J-box; this corrected the problem.

Crosscoupling was also found in merge and demerge areas, due to the merging or demerging loop signal being received off the side lobe of the vehicle antenna. Investigation revealed that due to loop and antenna geometry the crosscoupled signal might be detected and provide interference until the loop-to-loop spacing in the merge or demerge exceeded 15 in. Some loops were modified where feasible. Similar speed tone coupling had occurred in phase IA and required extension of many FSK/speed tone loops.

Stopping margins were analyzed also. It was found that stopping margins were safe, even with the crosscoupling.

Figure 3-19 shows the safe tone subsystem. The figure is applicable for phase IA/IB and phase II systems. No changes were made to the ICS station electronics for this subsystem in phase II.

3.2.2 Guideway and Loop Design

The MPM system uses a concrete running surface that can be either on grade or elevated. The inductive communications loops are located in slots cut into the concrete. Two sets of loops are used; up to three uplink loops are concurrently located one on top of the other in the slots on the right side of the guideway, and up to two downlink loops are located on the left side. Once the loops are placed in the slots they are covered over with an epoxy sealant for protection.

3.2.2.1 Loop Design

The objective of the guideway portion of the ICS is to provide a signal path from station electronics to vehicle electronics and back without any physical connection to the vehicle. This is done through inductive coupling of a.c. signals from current-carrying loops in the guideway to a multiturn receive antenna on the vehicle, similar to the primary and secondary of a transformer. As loops may vary from a few feet to nearly 1000 ft in length, it is essential that an efficient system be used to deliver the signal to the loops, thus minimizing losses and impedance discontinuities. Considering only signal delivery, it is feasible to consider the loop one portion of a transmission line; therefore, for long loops where higher frequencies are used, one must attempt to match the source to the feedline (twisted shielded pair), the feedline to the loop, then the loop impedance to a terminating impedance. For practical purposes, the termination impedance is purely resistive and for lower frequencies tends to mask out any reactive components of the loop.

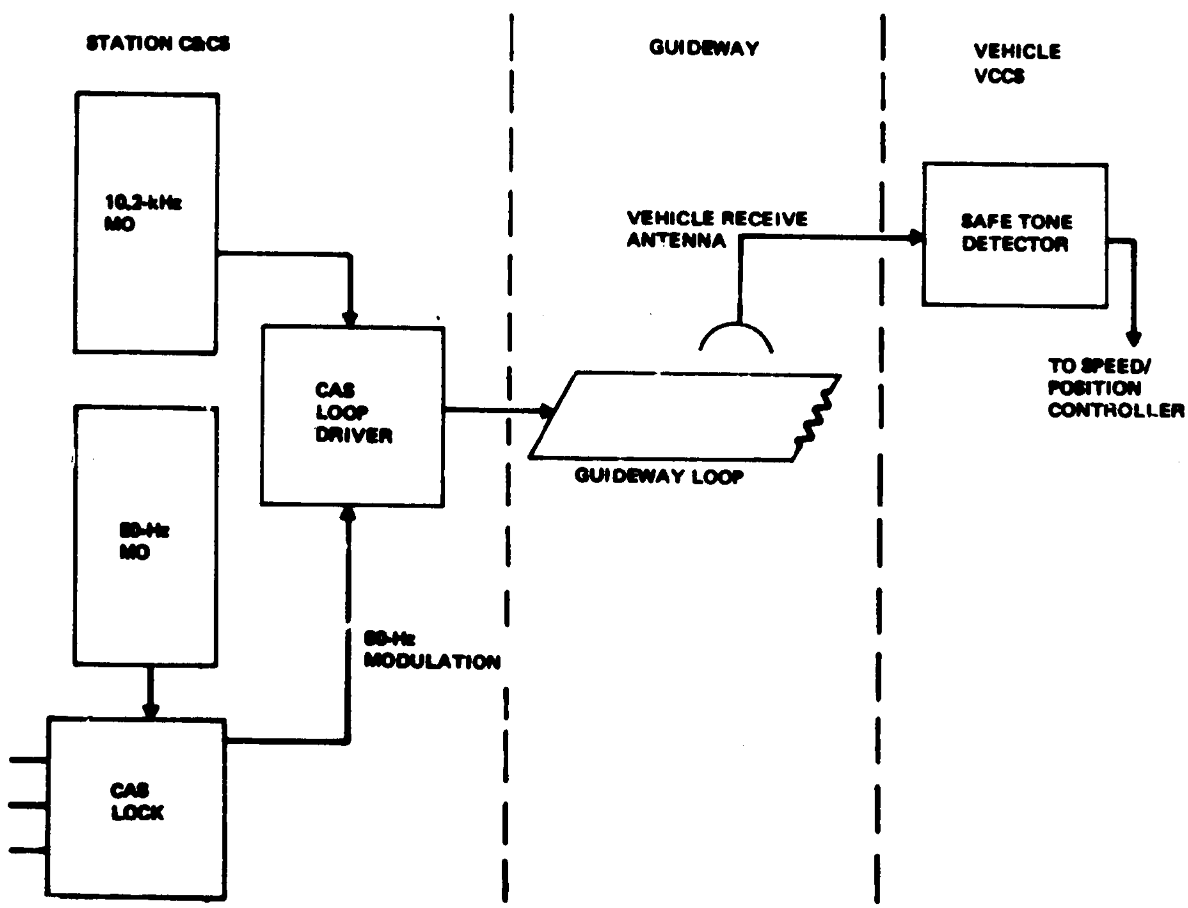


Figure 3-19. Safe Tone Subsystem (Part of CAS)

Once an efficient loop is designed and connected to a source of current the system can then be considered as a transformer with a single-turn primary (the guideway loop) and a multiturn secondary (the vehicle antenna). In this case, the concern becomes the degree of coupling or transfer impedance between the two antennas. The parameters most critical to efficient coupling are the loop and antenna width, antenna height and alignment, and antenna design (turn ratios, geometry, etc.). The downlink considerations are the same except the signal source is connected to the vehicle antenna and a receiver to the guideway loops.

Loop separation and antenna width varied from 4 to 8 in. in some of the early design concepts. The final configuration had loops 6 in. wide with a receive antenna approximately 4 in. wide. In general it was found that the optimum loop width was related to the desired antenna height above the guideway, and the width of the vehicle antenna was related to the expected tracking or antenna offset variation (a narrower antenna is less efficient but more forgiving of tracking variations).

Once the loop length and the physical dimensions are determined, the next tasks are selecting loop materials and implanting the loop in the concrete.

The material selected for the phases IA and IB loops was #14 AWG solid wire with a PVC insulation. The wire was installed using crimp type splices at the feedline-to-loop connection, at the terminating resistor (which also was buried in the slots), and for joining short lengths of wire as required. These materials and methods did not prove to be very reliable. In the phase II system a double-jacketed #16 AWG stranded wire was used with a standard inner insulation (crosslinked polymer preferred) and an outer nylon jacket (thus the outside diameter was the same as the #14 AWG used previously). The thicker insulation should provide better immunity to the perturbations of external environment such as water on the guideway, proximity of other wires, etc. The optimum splice is the Western Union type soldered splice with a mastic worked in for insulation. In the phase II system, splices have been eliminated in the buried portion of the guideway; wires are laid in a continuous segment, and all splices are made in the cable tray. The termination resistor is also located in the cable tray. Following loop installation the loops are sealed in place with a pliable hard-setting sealant.

The Morgantown loops were placed in slots cut in the concrete. The slots are 1/4 in. wide and 1/2 to 3/4 in. deep. The slots are parallel to and located about a loop centerline offset approximately 23 in. from the guideway centerline (fig. 3-20). It is essential that the loops be installed such that the vehicle antenna will track the loop centerline. In the phase IA and phase IB system the vehicles had a tendency to offtrack a fixed amount in certain tight-radius turns. Three attempts were made to change steering rail position to bring vehicle tracking back to normal. In the phase II portions of the guideway, the loops are being offset at installation to follow the vehicle on its predicted path thus reducing the tracking errors considerably.

3.2.2.2 Loop Balancing

As previously discussed, the Morgantown inductive communications system consists of one or more loops occupying the same guideway slots. Each loop contains discrete frequencies that may not be allowed to spill over or leak into the overlying or underlying loops such that the signal is detected outside of the area occupied by the transmitting loop. To accomplish this, loop-to-loop decoupling crossovers or phase reversals are added to selected loops to make the net energy coupled to other loops equal zero through cancellation. Figure 3-21 shows the simple case of two concurrent loops, one longer than the other. Signals transmitted by loop A are prevented from being retransmitted by loop B due to the crossover or phase reversal located at the exact center of loop A. Solid arrows show the instantaneous current flow in loop A; dashed arrows represent induced currents in loop B. The currents are coupled to loop B equally, but 180 deg out of phase, resulting in cancellation and no net current in loop B. In the real world, of course, the cancellation is incomplete and some net current remains. But, since loops A and B are not tightly coupled at MPM frequencies, the reradiated signal from loop B is kept 40 to 90 dB below the transmitted signal, putting it well outside the detection threshold of our receivers. Figure 3-22 shows a typical section of guideway.

The phases IA and IB systems used a crossover technique that picked the smallest sections of loop overlaps bounded by but containing no loop ends and balanced them each separately, resulting in good isolation but also in the maximum number of crossovers possible (see fig. 3-21). Since each crossover causes a momentary signal

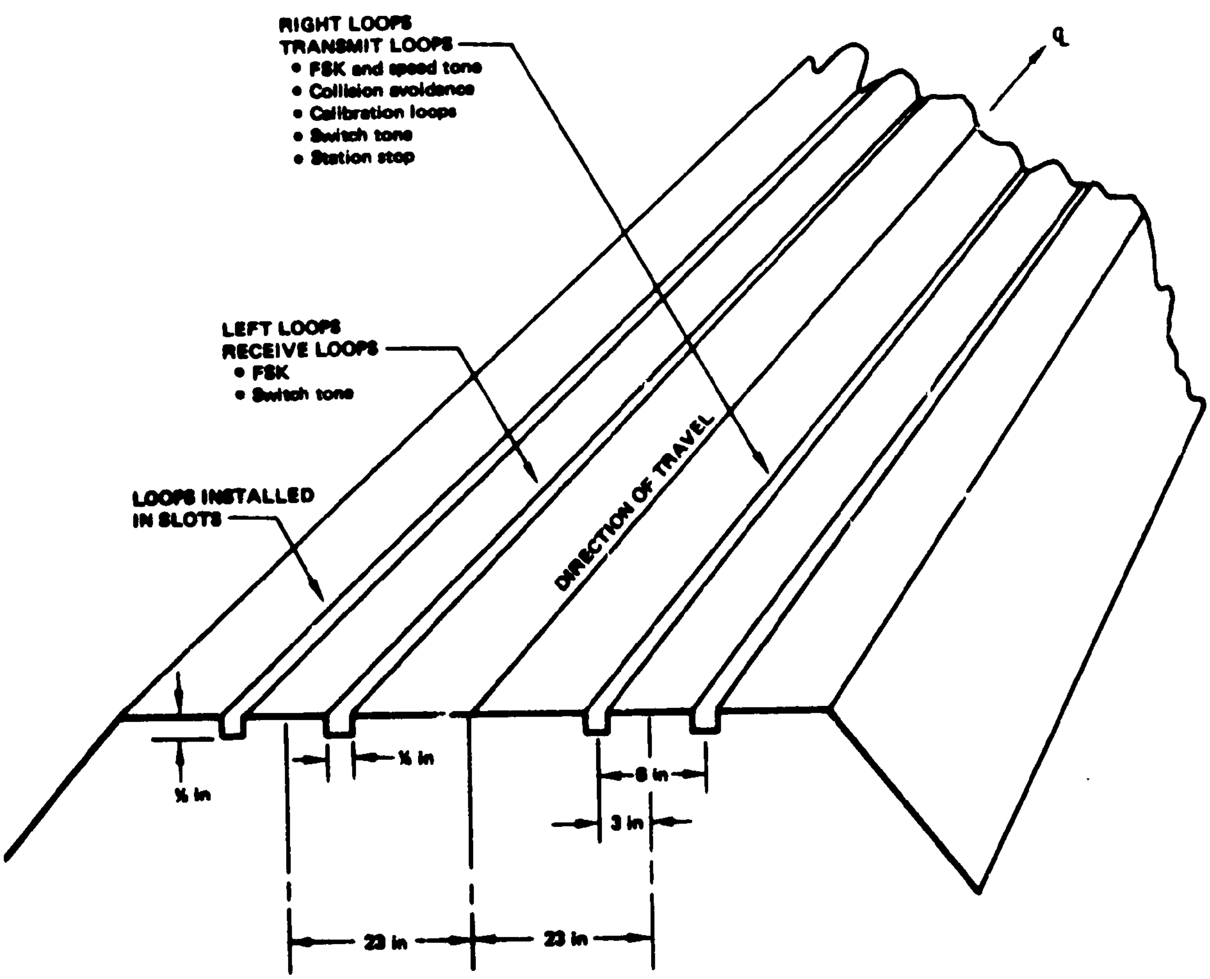


Figure 3-20. Loop Installation Plan

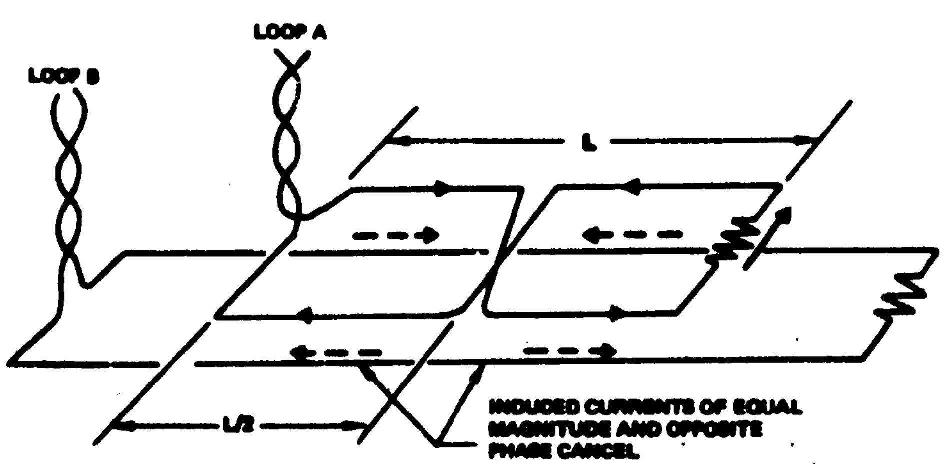


Figure 3-21. Loop Balancing

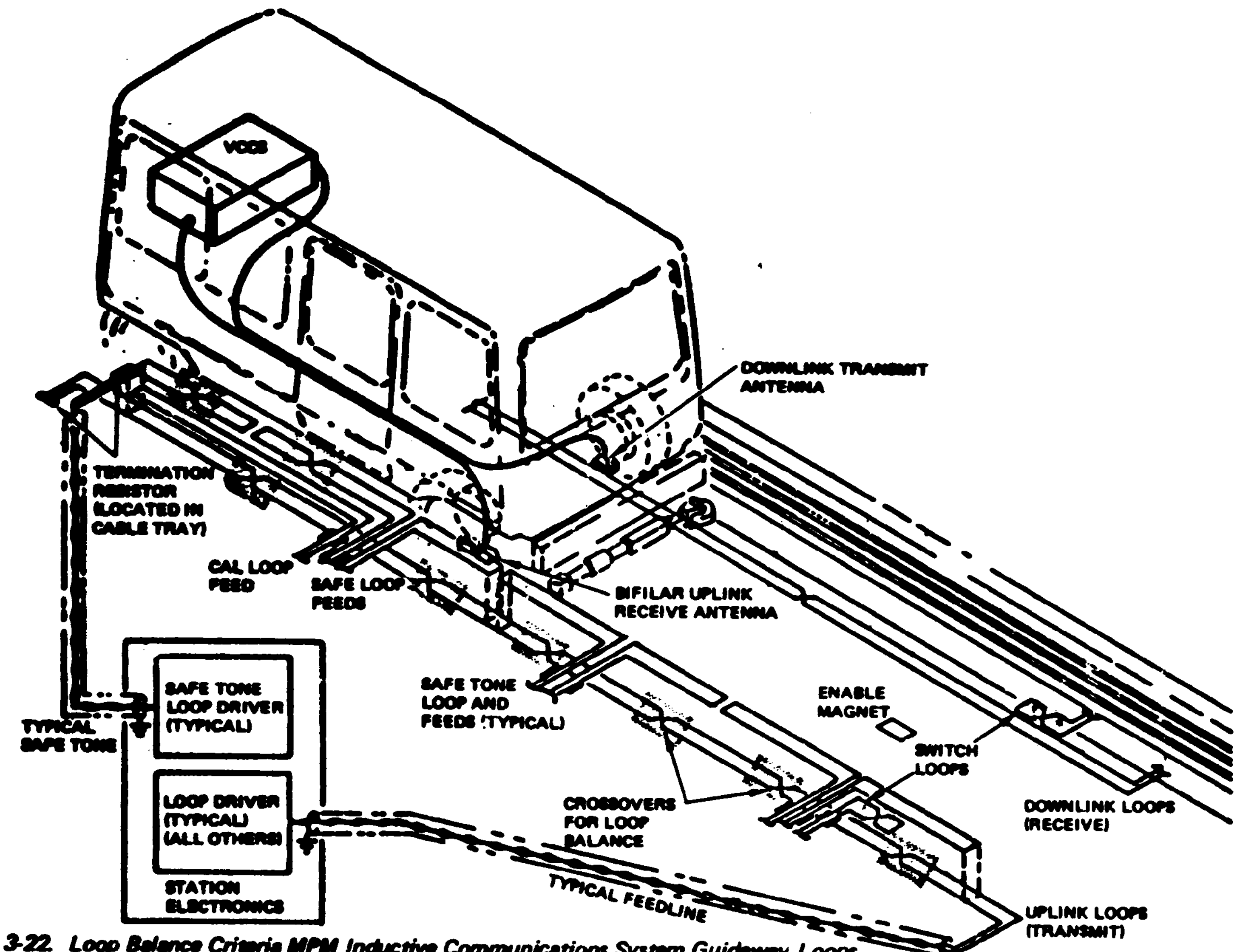


Figure 3-22. Loop Balance Criteria MPM Inductive Communications System Guideway Loops, Feed Lines, Car Antenna, Receivers, and Loop Drivers

loss that must be compensated for in the VCCS, it is desirable to reduce the total number of crossovers if possible. In phase II a system was devised that uses a computer program to balance much larger segments of the guideway simultaneously, thus allowing a 20% to 30% reduction in the number of crossovers while achieving the same degree of isolation. This will be discussed further in section 4.

3.2.2.3 Loop Failures and Guideway Problems

Following installation of the phase IA portions of the guideway the first loop problems identified were crossovers out of position or missing. The result was either higher than permitted leakage into adjacent loops or, in some cases, dropout of the transmitted signal. Examination of figure 3-21 shows that it would be possible to create a situation, with crossovers in incorrect locations, where the actual transmitted signal in loop A was supplemented by the reradiated loop B signal in one area or cancelled by the reradiated loop B signal in another area. Most of the sources of this type of unbalance were located and repaired in phase IA; the rest were found during phase IB rework.

The phase IB system Integration and Checkout (I&CO) began in 1974, several years after the phase IA loops were installed. During I&CO the loops exhibited an alarmingly high failure rate that was identified as failures in the crimp splices. Repairs were initiated and the splicing method switched to Western Union type splices. Other problems were attributed, at least in part, to loop failures resulting in low isolation to ground. Isolation tests using a 50V Megger were run, and loops with 10K ohms or less to ground were repaired. Most of the loop isolation failures were attributed to defective splices and sealant, abraded insulation (due to rubbing on the concrete from thermal expansion/contraction), and crushing in expansion joints. The loop expansion joint technique was revised, splice techniques were revised as mentioned, and for phase II the wire type was changed to an abrasion-resistant double-jacket type. Since all of the "open" type of failures have been attributed to broken splices and broken termination resistors that were buried in the guideway, splices in the guideway are eliminated in phase II and all resistors have been relocated to a less hostile environment in the cable trays.

The most significant loop failure occurred in January 1975. The incident occurred when a vehicle failed to switch after merging on the main guideway; minor damage to one vehicle resulted. Due to failure to switch the vehicle ran out of power and steering rail, causing it to attempt to steer hard right. The vehicle engaged a bumper rail on the side of the guideway and traveled along it until striking a support stanchion and coming to an abrupt stop.

An investigation of the incident revealed that it was caused by a crushing of several loop wires in an expansion joint several hundred feet away. A "switch right" loop at a demerge ramp was shorted to the overlying FSK loop, resulting in the "right" switch command being mixed with the FSK and speed commands on that loop. The vehicle involved in the incident, upon entering the FSK loop, was steering right on the merge ramp. As it entered the now defective FSK loop the vehicle simultaneously saw the inadvertent "steer right" command and the proper "steer left" command (from the switch loop in that area) and chose to remain in the "right" steering mode, thus losing power and steering rails. Tests later revealed that the VCCS, when presented with equal-magnitude "right" and "left" commands, exhibited a preference for the "right" command.

Following the incident all the expansion joints in the system were reworked to eliminate the possibility of crushing wires. In addition, the steering rail runouts following switch loops were lengthened and power rails shortened to allow an incorrectly switched vehicle to come to a "normal" brake stop while maintaining steering control following loss of power. Extensive work was done on the guideway loops (as previously discussed) to upgrade their integrity. To preclude the possibility of an inadvertent speed command being issued in the same manner, the high/low speed enable modification (previously discussed) and the synchronization of certain speed loop modulations and high/low speed enable magnets were added. Also, a steering-rail-mounted detection switch was added in the phase II guideway area to back up the switch verification system by commanding emergency brakes to any vehicle that has failed to switch and not been caught by the CAS.

In the phase II program a major emphasis was put on maintaining high integrity of the wire during initial installation. This, along with the elimination of splices, relocation of the termination resistor to the cable tray, and use of a wire more impervious to abrasion and insulation breakdown, is expected to ensure an extremely reliable buried-loop system in the phase II portion of the guideway.

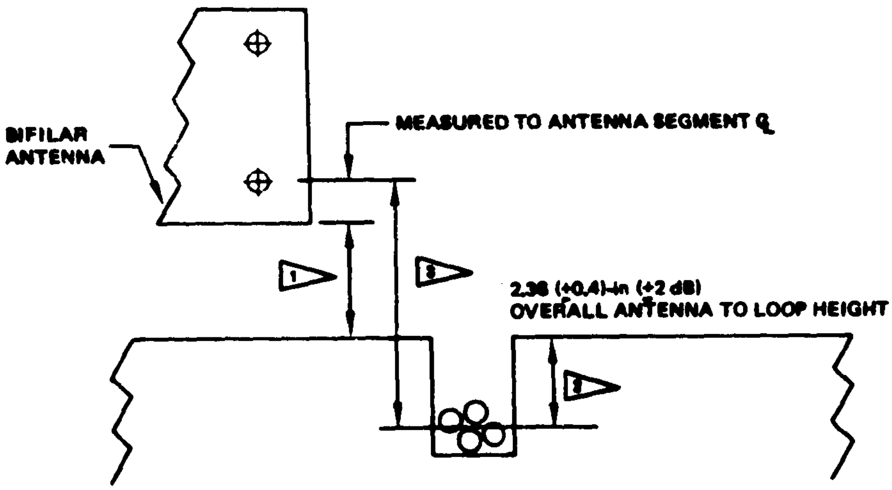
3.2.3 Vehicle Antennas

There are two receiving antennas and one transmit antenna mounted on the MPRT vehicles near the front axle. The antennas are located approximately 1.8 in. above the guideway surface and are mounted such that they track the nominal loop centerline. Each antenna is designed to take into account the hostile environment under the vehicle.

Early trade study concepts had considered a core-type antenna, but the rectangular loop was used in phase IA. The two uplink receiving antennas were mounted in line with their lateral centerlines about 8 in. apart. Each antenna was connected to an independent set of receivers in the VCCS, thus ensuring continuous reception of command signals even while passing over crossovers, loop ends, etc. The VCCS will recognize loss of a command only when both antennas lose it simultaneously. On the downlink side, there was only one transmit antenna because the downlink FSK messages are less critical (and are repeated three times). The antennas were to have a self-resonant frequency greater than 150 kHz and be mounted on adjustable brackets. Antenna vertical and lateral requirements are shown in figures 3-23 and 3-24.

Phase IA problems were related primarily to antenna tracking and alignment. An average vehicle tracked nearly 3/4 in. to the right whether biased right or left. This became worse on curves. Some problems with antenna yaw also were encountered. Noise coupling problems existed, but were not fully recognized until the phase IB program. The tracking problems were addressed in the phase IB vehicle by revisions to the suspension and steering systems.

The noise problems were more evident in phase IB, and the magnetic coupling from the a.c. power wiring to the VCCS antenna became suspect. The VCCS receiving antenna was within this field and resulted in considerable coupling. Rerouting, twisting, and shielding of the power wires were of some help. The design of a vertical bifilar receive antenna (fig. 3-25) was undertaken to further reduce noise coupling.



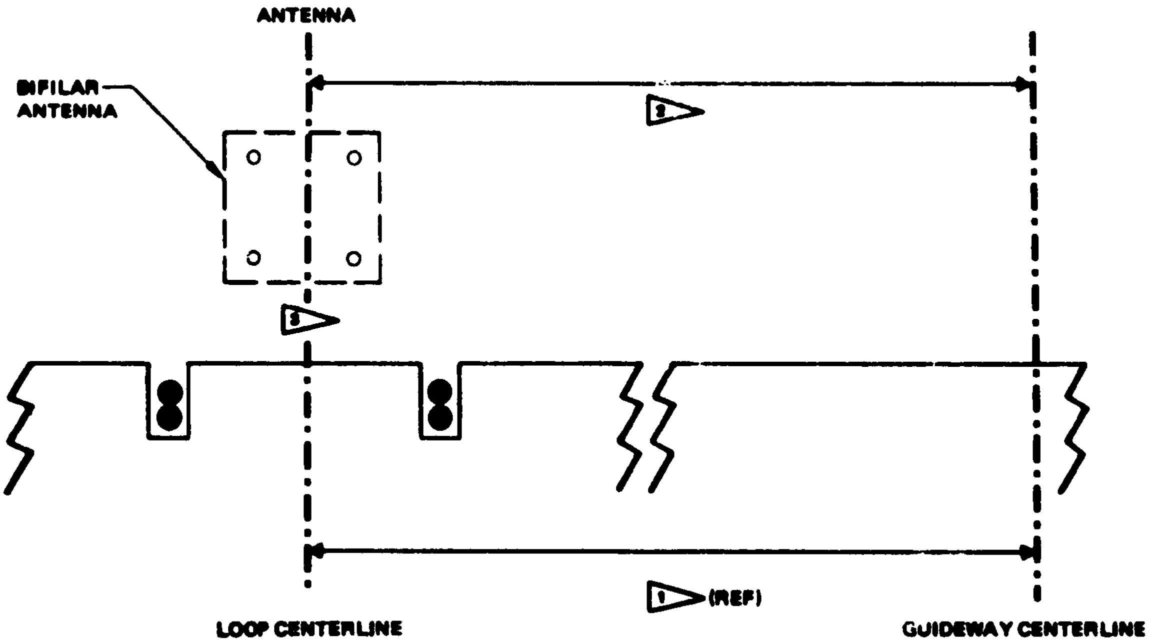
Note: Tolerance on [2] is due to wire position uncertainty.

[1] Antenna body to guideway surface = 1.8 (±0.2) in (flat-tire condition not included)
- Tire condition and tread depth
- Antenna mounting variations
- Guideway surface irregularities

[2] Loop depth below surface = 0.25 (±0.2) in
- Wire position uncertainty
- Slot depth tolerances

[3] Overall antenna to loop height = 2.36 (±0.4) in (±2 dB) and includes [1] and [2], the correct height measurement for all signal calculations.

Figure 3-23. Antenna Height Above Loop Wire



1. Loop centerline is 23 (±0.86) in from guideway centerline.
2. Bifilar antenna should track guideway loop centerline within 0.0 (±1.0) in (sum of all vehicle variations, 22 (±0.86) in from guide rail)
3. Actual offset used for margin calculations is offset of antenna centerline from guideway loop centerline. This should be no greater than 0.0 (±1.9) in (-2 dB):

   ±1 in due to vehicle variations
   ±0.86 in due to guideway variations

Figure 3-24. Antenna Lateral Position (Offset)

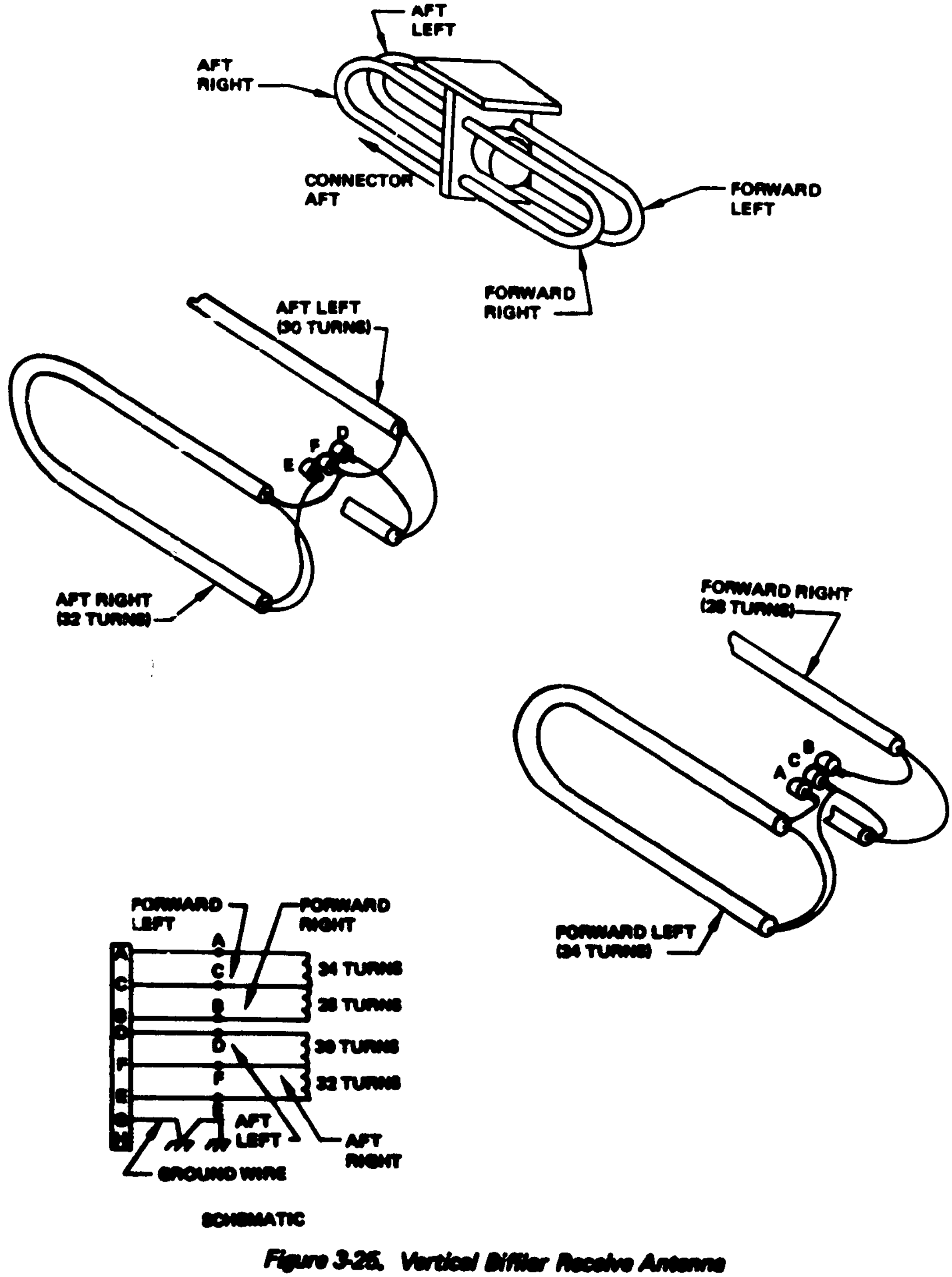


Figure 3-25. Vertical Bifilar Receive Antenna

The computer model used in the antenna design analysis predicted a worst-case signal coupling reduction of 5.6 to 8.6 dB when the bifilar antenna was substituted for the rectangular antenna. It was also determined that coupling for lateral displacement of the antenna was different. The null, occuring as the antenna is moved laterally over the loop wires, was moved closer to the loop centerline making lateral offtracking more critical. The side reception became better, making crosscoupling greater at merge and demerge areas. The bifilar antenna was adopted even with this lower peak coupling and higher signal falloff rate with lateral displacement, since it provided noise reductions of 10 to 15 dB during power switchover and when on station ground, thus ameliorating the noise problem. One other side effect of the bifilar, not fully realized at the time, was that its end effects were sufficiently different from the rectangular to cause later acquisition of the stop tone and thus a resulting overshoot of the berthing position.

Figure 3-26 shows the differences in end effect between the rectangular antenna and the vertical bifilar. The vertical scale is signal output in millivolts and the horizontal is antenna centerline displacement longitudinally with respect to a crossover or loop end. Note that antenna assembly centerline will be offset about 4.5 in. from receiving loop centerline. Figure 3-27 compares antenna receptions with lateral displacement.

After compensation for the aforementioned disadvantages, the overall performance of the bifilar antenna has been significantly better than the rectangular unit in a noisy environment.

3.2.4 VCCS Design

The VCCS is that part of the C&CS carried aboard the vehicle. It provides the signaling control interface between the guideway signals and the vehicle actuators. The VCCS contains the following functional units: communications, data handling, control, and support. Our primary concern is with the communications unit. The uplink portion of the VCCS communications unit contains 16 receivers, some of them redundant, fed from the forward and aft sections of the vehicle receive antenna. The downlink section contains a transmitting unit supplying FSK and switch verification signals to the vehicle transmit antenna.

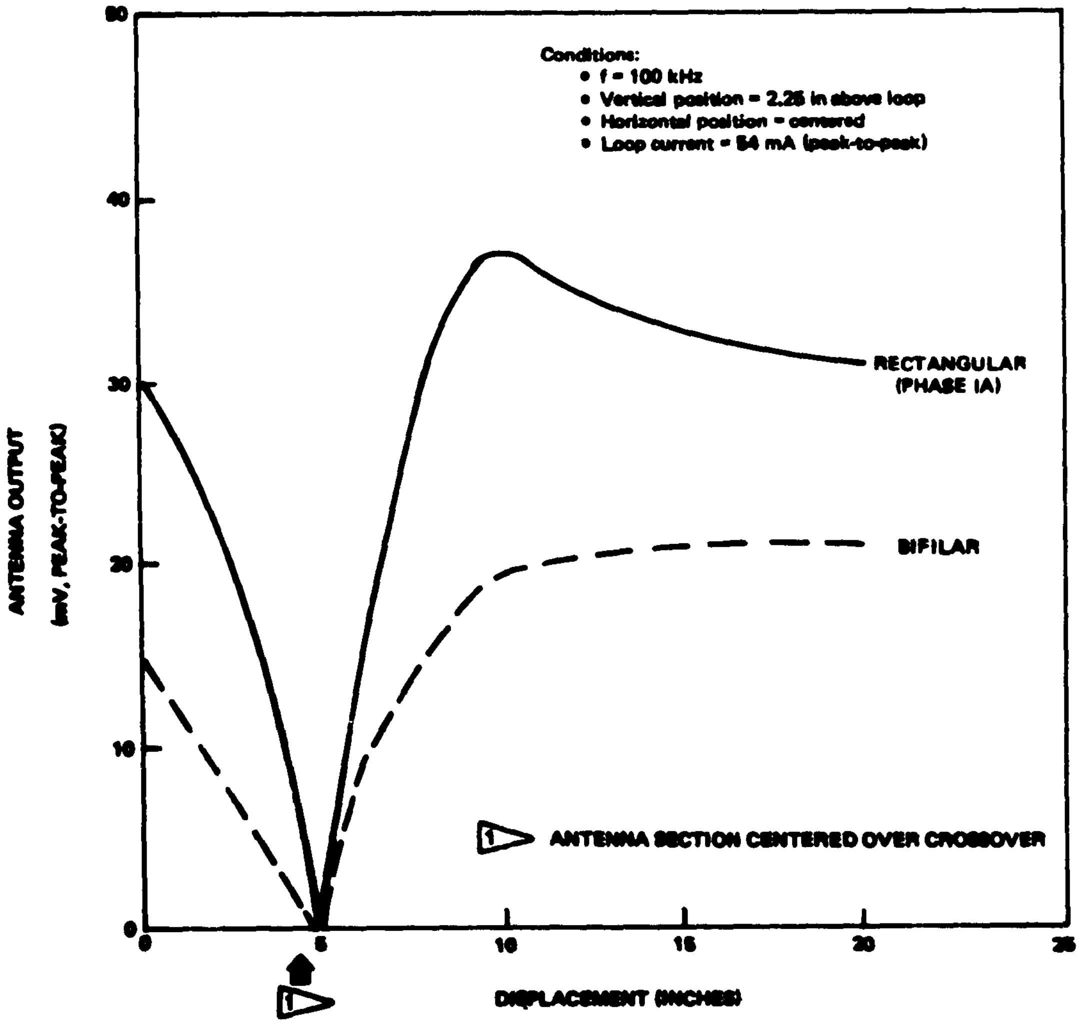


Figure 3-26. Antenna Output Versus Longitudinal Displacement

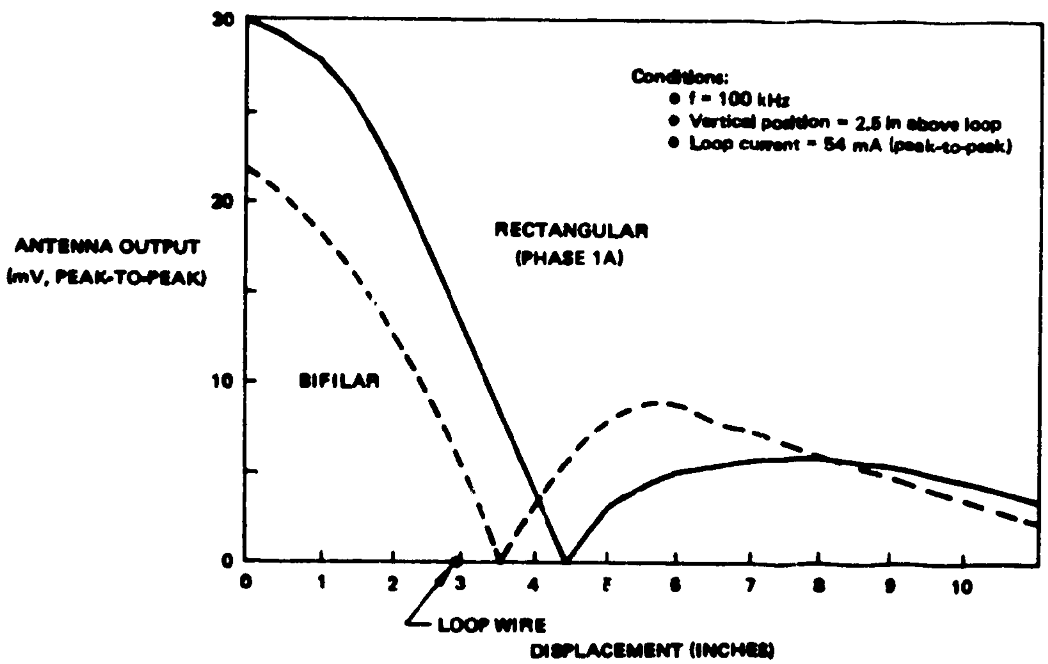


Figure 3-27. Antenna Output Versus Lateral Displacement

Early concepts of the VCCS had some additional equipment, such as a reverse tone receiver and amplifier that also would have been used to receive the ramp profile tone and an emergency communications unit that would have allowed passenger voice communications over the inductive communications system. These items were deleted prior to phase IA.

Frequency and modulation selection for the control system receivers paralleled the station electronics development; the final allotments are those shown in table 3-10. The calibration tone was 50 Hz modulated in the phase IA system, but this was deleted for phase IB because it detracted from the accuracy.

Numerous problems were encountered with the phase IA VCCS; most have been discussed in some detail in the subsystem sections. Three communications problems appeared to plague the early VCCS. The first was inconsistency in station stopping. Vehicles were not stopping within the required tolerance at berth locations. The second was erroneous VCCS downlink messages. Many were caused by speed tone dropouts at transitions and some were from intermittent vehicle-generated fault signals. The last problem was the marginal operation of all communication channels, caused mostly by insufficient signal levels on the guideway and system-generated noise. The uplink FSK channel was particularly susceptible.

TABLE 3-10. MPM COMMUNICATIONS FREQUENCIES

TONE FREQUENCY USE CHART
NUMERICAL ENTRIES ARE MODULATION FREQ
MODULATION IS 100% SQ WAVE 50% DUTY CYCLE

COMMAND/SIGNAL NAME	CARRIER FREQ kHz	6.1	10.2	13.3	17.2	22.0	28.3	36.3
SPEED 44 FPS		50		50				
SPEED 33 FPS				50	50			
SPEED 22 FPS		50			50			
SPEED 8 FPS		50						
SPEED 6 FPS				50				
SPEED 4 FPS					50			
SAFETONE			50					
SWITCH COMMAND RIGHT							50	
SIWTCH COMMAND LEFT							70	
SWITCH VERIFY RIGHT						50		
SWITCH VERIFY LEFT						70		
CALIBRATE								TONE ONLY
STATION STOP								TONE ONLY
UPLINK FSK DATA "1" DATA "Ø"	 129 kHz 121 kHz							
DOWNLINK FSK DATA "1" DATA "Ø"	 104 kHz 96 kHz							

(UPLINK FSK and DOWNLINK FSK:) 1 kHz BIT RATE, 50% DUTY CYCLE.

The following VCCS items were scheduled for redesign in the phase IB program: (1) FSK transmitter unit, (2) data sequencer, and (3) brake and motor control. In addition, high failure rates were experienced in digital-to-analog converters and 22-kHz crystal oscillators (similar to oscillator failures occuring in the station electronics). In actuality the entire VCCS was redesigned for phase IB as a result of switching the design task to Boeing.

Data were obtained from phase IA communication signal levels via magnetic tapes taken during actual vehicle operation. These tapes were analyzed and the resulting data used to develop nominal characteristics and thresholds for the new VCCS. The general result was the design of a much more sensitive set of receivers, using phase lock loops for all channels except FSK. The new VCCS was placed on the Seattle test track for system testing in January 1974, and it became immediately apparent that with the new sensivity system noise levels had become a serious problem.

Noise problems were grouped into several categories: system-generated spurious signals (harmonics, intermodulation products, etc.), vehicle-generated noise (SCR spikes, etc.), and power-system-generated noise (inrush transients at turn-on, fourth rail safety ground noise, switching noise due to current imbalances at switching, etc.). As previously discussed, many system changes were made to address this noise problem; e.g., the addition of the bifilar antenna, design changes to selected station electronic components, vehicle power rerouting, and filtering of the fourth rail safety ground. Changes also were made to the VCCS that resulted in a shifting of thresholds and sensitivities in the various channels and to the FSK receiver to provide it with a minimum signal threshold, thus limiting its sensitivity to spurious signals. The threshold levels of the new receiver were defined by setting "accept" and "reject" criteria. Signals must exceed the "accept" level for detection, and all spurious signals must remain below the "reject" level to prevent detection. The phase IB levels are shown in table 3-11.

In at least one case it was found that noise impulse levels approached the damage threshold of the receiver. The noise from power inrush transients at turn-on and from ground rail dispatch noise was investigated at the input to the VCCS; noise was excessive in the 28.3-kHz passband.

TABLE 3-11 VCCS THRESHOLD LEVELS (PHASE IB)

CHANNEL	FREQ kHz	VCCS SPEC. MUST REJECT (mV_{p-p})	VCCS SPEC. ACCEPT RANGE (mV_{p-p})	C[illegible]CS SPEC. MAX. SPURIOUS (mV_{p-p})	REMARKS
SPEED TONES					
A	6.1	1.0	5.0-30.0	1.0	
B	13.3	1.1	8.0-40.0	1.1	
C	17.2	2.0	11.0-56.0	2.0	
SAFETONE	10.2	0.5	4.0-34	.25	
SWITCH TONE	28.3	3.5	10.0-50.0	1.8	
CAL/STOP TONE	36.3	2.6	13.0-60.0	2.6	
FSK	121/129	1.0	12.0-260.0	1.0	Noise must be 8 dB below "ON" level during msg.

An unfortunate result of the derived accept/reject criteria was the necessity to "hand-sort" the phase lock loops used in certain receiver channels to narrow the overall gain and threshold variations from receiver to receiver. Figure 3-28 shows the final communication system signal interface criteria. The VCCS maximum signal level is the point beyond which input stage harmonic and intermodulation figures could not be guaranteed. The "must accept" and "must reject" levels have been previously described. The nominal loop set point governs loop adjustment and is intended to be the average transmitted signal on the guideway. Lastly, the maximum spurious level is the highest level that any spurious interfering signal can be at any point on the guideway. Harmonics and signal leakage are the primary concern. All signal levels are measured in reference to the input to the VCCS.

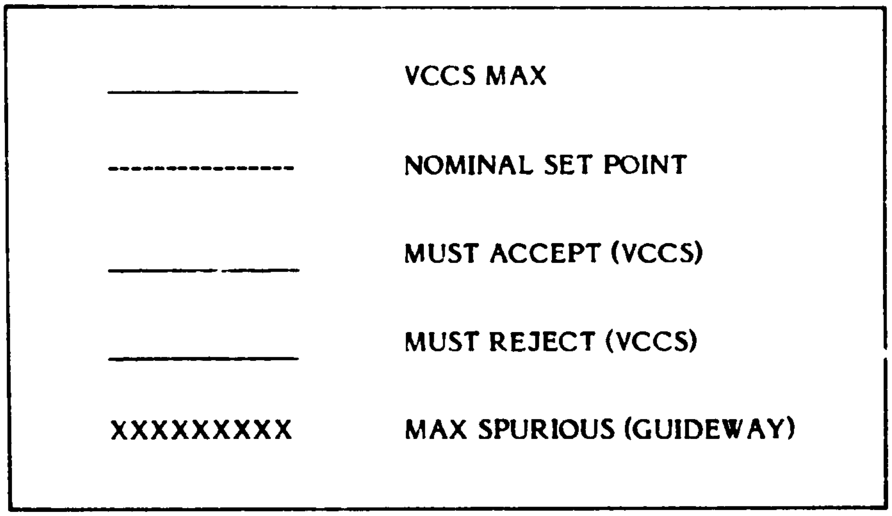


FIGURE 3-28. COMMUNICATION SYSTEM INTERFACE CRITERIA

Changes to the system during phase IB and modifications made to the station electronics for phase II will help to ensure a highly reliable communication system. Changes made to the VCCS in phase II were limited to resolving parts reliability problems and vastly expanding the downlink fault reporting function. Figure 3-28 shows the faults reported in the phase IA/IB systems. Many of these messages were the product of "or-ing" numerous internal VCCS and vehicle faults. As a result it was felt that insufficient data were being communicated on the exact nature of faults within the VCCS. In phase II the data bits corresponding to the "fault report" function code have been converted from a dedicated one-bit-per-fault format to a binary format, allowing much greater visibility into vehicle operation (table 3-12). Those faults shown as delayed are those that are by nature intermittent, and the delay allows reporting only the hard failures. Figure 3-29 shows the final configuration of the vehicle control and communication subsystem.

Table 3-12 CONTENTS OF DATA FIELD FOR IDENTITY REPLIES AND FAULT REPORTS

Delayed Fault	FUNCTION	DATA FIELD BIT 10	11	12	13	14	15
	NO FAULT	0	0	0	0	0	0
	EXITS NOT CLOSED*	1	X	X	X	X	X
	HYD #1 or 2 ACCUM. LOW	X	1	0	1	1	0
D	VEHICLE SPARE	X	0	0	0	0	1
	VEHICLE OVERTEMP WARN	X	1	1	1	1	0
	BRAKE OVERTEMP	X	0	0	1	1	0
	PRO CONT ZERO PERF	X	1	1	0	1	0
	PROP CONT LOSS OF PRIME POWER	X	0	1	0	1	0
D	LOSS OF BRAKE REDUND	X	1	1	1	1	1
D	BATTERY VOLT LOW	X	0	1	1	1	1
D	PROP CONT REDUCED PERFORMANCE	X	0	1	1	1	0
D	SPARE	X	1	0	1	1	1
D	SPARE	X	0	0	1	1	1
D	PNEUMATIC PRESS WARN	X	1	1	0	1	1
D	HYDRAULIC TEMP WARN	X	0	1	0	1	1
	LOSS OF SAFETONE #1 or #2	X	1	0	0	1	0
	OVERSPEED #1	X	0	0	0	1	0
	OVERSPEED #2	X	1	1	1	0	0
	UNDERSPEED #1 or #2	X	0	0	1	0	0
	LOSS OF ODOMETERS CH.1 OR CH.2	X	0	1	1	0	0
	POWER OUT OF TOL CH.1 OR CH.2	X	1	0	1	0	0
D	CAL FACTOR LIMIT EXCEEDED CH.1	X	1	1	1	0	1
D	CAL FACTOR LIMIT EXCEEDED CH.2	X	0	1	1	0	1
D	POSITION ERROR LIMIT EXCEEDED	X	1	0	1	0	1
D	ILLEGAL CIVIL SPEED CH.1	X	1	0	0	1	1
D	ILLEGAL CIVIL SPEED CH.2	X	0	0	0	1	1
D	MOTOR SIGNAL DISPARITY	X	0	0	1	0	1
D	BRAKE SIGNAL DISPARITY	X	1	1	0	0	1
D	EMERGENCY STOP RELAY DISPARITY	X	0	1	0	0	1
D	STEERING RELAY DISPARITY	X	1	0	0	0	1
	HIGH SPEED ENABLE DISPARITY CH.1 OR CH.2	X	1	1	0	0	0
	NOT USED	X	1	1	1	1	1

*PRIORITY FAULT REPORT (CAN BE REPORTED SEPARATELY OR IN CONJUNCTION WITH ANY OTHER FAULT)

X = DON'T CARE: CAN BE EITHER 1 OR 0.

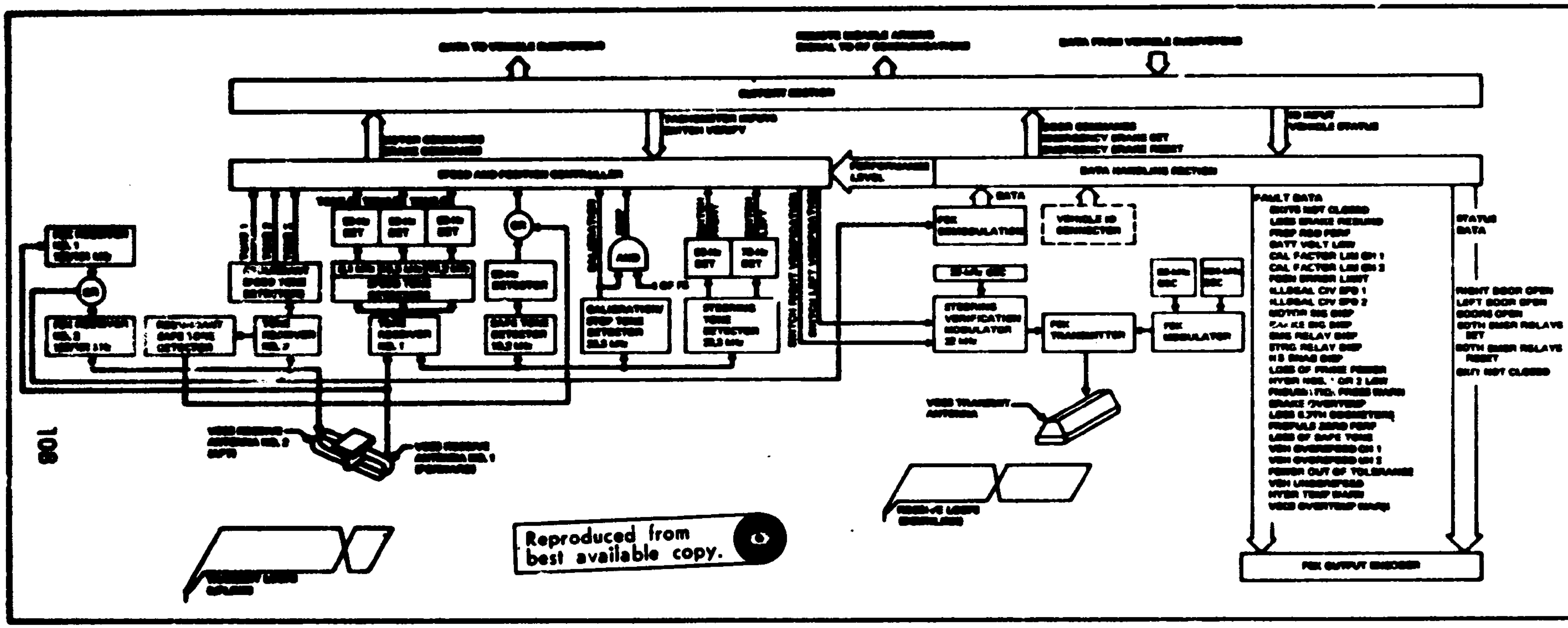


Figure 3-28. Vehicle Control and Communications Subsystem

3.2.5 Signal Levels and Margins

Review of early Bendix and JPL design data shows that the signal-to-noise ratio design goal varied between 15 and 20 dB. The MPM system was plagued from the beginning by a lack of margin and, in many cases, signal levels that were lower than expected. Part of the problem stemmed from link losses that exceeded estimates, which necessitated circuit cards to be adjusted in excess of their design capabilities, causing high distortion. Also, signal leakage levels and receiver noise thresholds appeared less than optimum in the face of noise levels higher than anticipated.

The primary communication signal interface point was the VCCS input/output, and it is with reference to this point that all later signal levels were given. Table 3-13 shows the progression of signal "accept" and "reject" thresholds for the VCCS receivers from early phase IA through phase II design. The final phase II specification reflects the total of all changes through the phase IB program.

At least two attempts were made to accurately measure the as-built guideway signal levels and thus predict signal margins. In August 1973, measurements were made using wideband magnetic tape recorders. Data were analyzed and published in a communications study as part of the Morgantown communication completion plan. The goal of the plan was to develop a communications link model using existing data, supplemented by additional measurements and analysis. The results were to be used to predict system performance and provide guidelines for the phase IB VCCS design. In late 1974, further measurements were made to better characterize the total noise picture in response to problems being encountered during the test phase of the program. Several VCCS threshold changes were made as a result of this and other testing, along with changes to reduce the noise at its source or reduce coupling.

One of the major results of the phase IB communications study was the realization that, at FSK frequencies, significant standing waves existed in the longer loops. Guideway adjustment procedures were reevaluated, and signal level mapping at periodic intervals along the guideway was instigated as part of the adjustment procedure to ensure that all segments of the loop were within the VCCS dynamic range and that the total end-to-end variation due to standing waves and other causes is also within limits.

TABLE 3-13. VCCS RECEIVER SIGNAL LEVEL REQUIREMENTS (UPLINK)

FUNCTION	FREQ.	ØIA SPEC SEPT '73		ØIB SPEC MAY '75		ØII	
		ACCEPT	REJECT	ACCEPT	REJECT	ACCEPT	REJECT
		mVpp	mVpp				
Speed Tone A	6.1 kHz	8.2	-18dB 1.03	5.0	1.0	5.0	1.0
Speed Tone B	13.3 kHz	8.6	-18dB 1.08	8.0	1.1	8.0	1.1
Speed Tone C	17.2 kHz	11.6	-18dB 1.5	11.0	2.0	11.0	2.0
Safe Tone	10.2 kHz	6.4	-18dB 0.81	4.0	1.0	4.0	1.0
Switch Tone	28.3 kHz	12.3	-18dB 1.5	10.0	3.5	10.0	3.0
CAL&Stop Tone	36.3 kHz	13.2	-18dB 1.7	13.0	2.6	13.0	2.6
FSK Uplink	121 kHz	6.0	-18dB .75	12.0	1.0	12.0	2 (1)
(DATA)	129 kHz	6.0	-18dB .75	12.0	1.0	12.0	2 (1)

(1) Adjustable from 1 - 2 mV_{p-p}.

For phase II an extensive evaluation was done to determine all variables in the system and account for each in the margin calculations. Section 4 will discuss the actual margin calculations in detail; however, it would be valuable to look at what "margin" means at this point. Figure 3-30 shows the methods used to calculate signal margins. The VCCS threshold specifications are shown along the left side for comparison. The three hardest parameters to determine were (1) the total loop signal variation due to standing waves, link losses, etc.; (2) the total vehicle variation, including such things as tire pressure, antenna offtracking, and vehicle oscillations; and (3) the noise floor for each individual portion of the frequency spectrum used.

3.2.6 Design and Development Summary

The communications problems encountered and the corrective actions that were taken are summarized on the following pages.

Summary of Problems

a. Early model did not accurately predict link losses; therefore, insufficient drive was available from the station electronics without excessive distortion. Delicate adjustment procedures were necessary to balance gain against distortion.

b. Harmonics of lower frequency signals appearing within the passbands of the higher frequency channels were a source of interference (table 3-14), due in part to high-frequency emphasis of the inductive link.

c. Leakage of 121- and 129-kHz tones was present due to extensive rework of cards and inadequate shielding, which caused interference with FSK messages.

d. Low guideway signal levels were due to loop geometry, standing waves, crosscoupling, and loop installation errors.

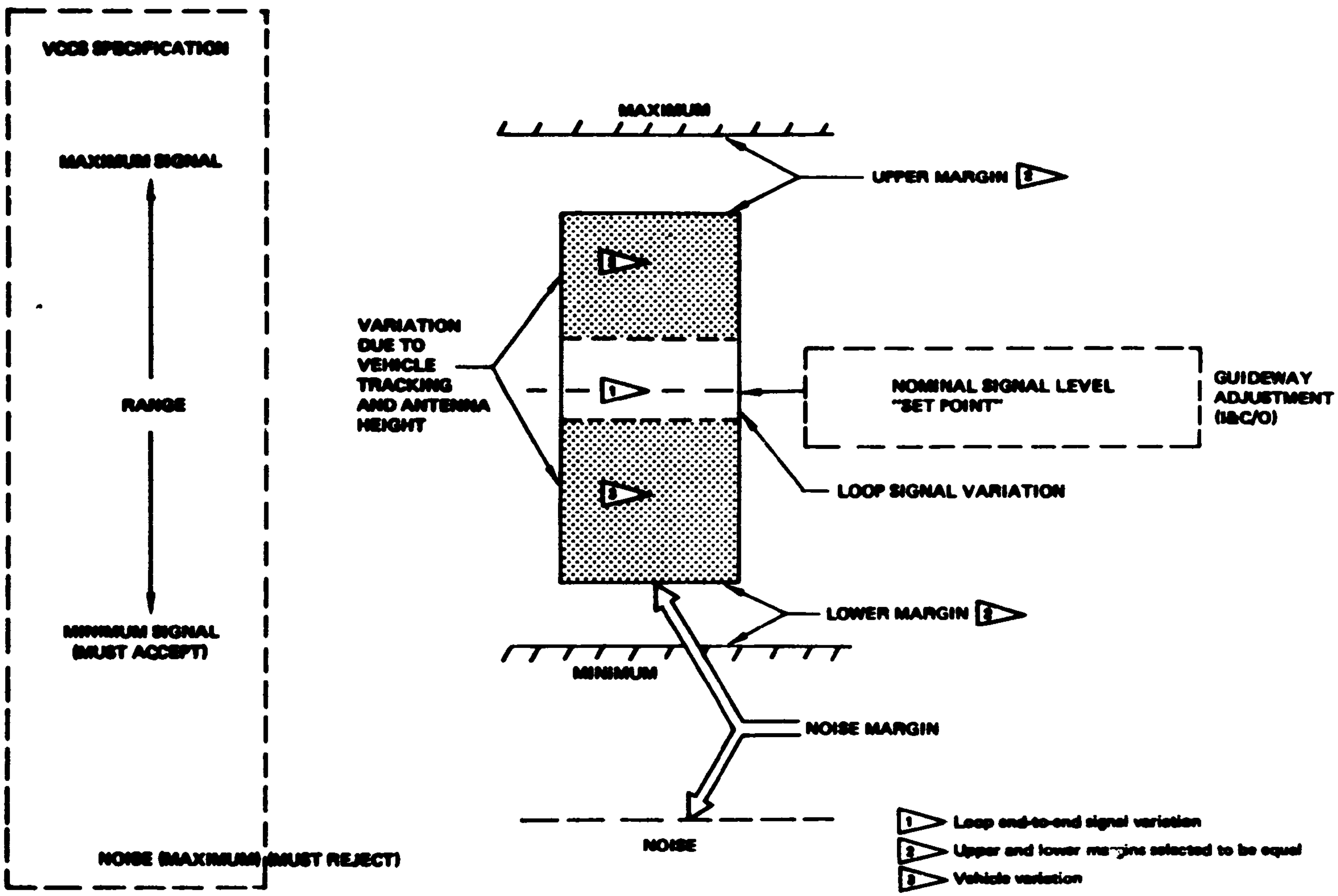


Figure 3-30. Method of Calculating Margin

TABLE 3-14 HARMONICS FALLING IN OR NEAR VCCS PASS BANDS

FUNDAMENTAL	HARMONIC	FREQUENCY (KHz)	CHOPPING FREQUENCY (Hz)	VCCS PASS BAND WITH POSSIBLE INTERFERENCE
Speed Tone "A" 6.1 kHz	3rd**	18.3	50	Speed Tone C (17.2) ▷1
	5th	30.5	50	Switch Tone (28.3)
	6th**	36.6	50	Cal/Stop (36.3) ▷2
	20th*	122.0	50	FSK 121 kHz } ▷3
	21st*	128.1	50	FSK 129 kHz } ▷3
Speed Tone "B" 13.3 kHz	2nd	26.6**	50	Switch Tone (28.3) ▷4
	9th**	119.7	50	FSK 121 kHz ▷3
Speed Tone "C" 17.2 kHz	7th**	120.4	50	FSK 121 kHz ▷3
Safe Tone 10.2 kHz	3rd	30.6	50	Switch Tone (28.3)
	12th	122.4	50	FSK 121 kHz

EFFECT OF INTERFERENCE

▷1 Will cause failure to recognize Speed Tone C resulting in improper speed and probable anomaly reaction.

▷2 Causes poor regulation due to failure to recognize valid calibration loops or attempts to calibrate (or stop) where cal/stop loops are not present.

▷3 Presence of invalid tone prevents FSK communication.

▷4 This case, probably the worst problem, simulates a right switch signal which usually will result in an availability problem.

* Harmonics not considered to be significant.
** Most significant harmonics, previously observed interference.

e. Noise levels were higher than anticipated—
   1. During switching when both collectors were out
   2. In station areas due to power inrush at turn-on
   3. During vehicle acceleration in station areas due to motor SCR noise and current imbalance
   4. On the fourth rail safety ground in station areas

f. Vehicle offtracking was greater than anticipated. System tolerance to offtracking was minimal due to marginal levels. Sensitivity of the system to offtracking increased due to the use of the bifilar antenna.

g. Safe tone and speed tone problems were caused by (1) crosscoupling at merges and demerges due to proximity of segments of loops and (2) side lobe coupling on the antennas.

h. Low signal levels due to cancellation of the desired signal were caused by out-of-position crossovers due to installation errors.

i. High failure of guideway loops occurred, due to use of a nonruggedized wire, ineffective splicing techniques, and damage during installation.

Summary of Corrective Actions

Corrective action on these problems has been an evolutionary process. Effects of some fixes were later negated by correction of other problems or groups of smaller, less significant changes that were incorporated in a larger redesign. The following list includes some of the more significant design actions that had a lasting beneficial effect.

a. Excessive link loss, insufficient drive from station electronics:
   1. Design changes were initiated in the loop driver and FSK transmitter to optimize their performance.
   2. Accumulated data on link performance were evaluated, and an accurate model was derived.
   3. VCCS was redesigned to improve dynamic range and sensitivity.
   4. New designs for loop driver and FSK transmitter were incorporated in phase II; actual system requirements, derived from experience analysis, will be met.

b. Excessive harmonics:

1. Adjustment procedures were developed that used spectrum analyzer to balance gain versus distortion and to ensure that interfering signals are kept below thresholds.
2. Design changes were made to existing station electronics circuits to reduce distortion.
3. Phase II system incorporated designs with extremely low distortion even at maximum operating capabilities.

c. FSK signal leakage:

1. High-frequency roll-off was added to the loop driver and the desired signal level was increased in earlier stages to get greater signal-to-leakage ratio.
2. Phase II design incorporated a new FSK transmitter card with low leakage levels. Also, common-mode rejection of interface circuits was improved and extensive shielding was incorporated throughout the drawer and rack design.

d. Low guideway signals:

1. Adjustment procedure was developed that incorporated mapping to ensure that the standing wave was centered in receiver dynamic range.
2. Loop installation errors found from mapping and guideway signal evaluation were corrected.
3. New installation techniques were developed in phase II to reduce errors and signal variations.
4. Phase II loop driver transformer was coupled to loop to provide efficient match.

e. High noise levels:

1. Numerous changes were made to power and vehicle subsystems to reduce noise at source.
2. Bifilar receive antenna was incorporated to reduce coupling to power and ground system.
3. VCCS thresholds were changed to make receiver more tolerant of existing noise levels (hand sorting of PLL's).

f. Vehicle offtracking:

1. Antenna alignment on vehicle was adjusted to closer tolerances.
2. Excessive offtracking problems in some turns were corrected by realigning the steering rail.
3. Vehicle design was changed to improve tracking.
4. Tracking specification was changed to ± 1 in for phase II.
5. Phase II loops were intentionally offset to anticipated vehicle antenna path.

g. Crosscoupling:

1. FSK/speed loops were lengthened where required to avoid interference.
2. Safe tone loops were lengthened where possible to avoid unintentional emergency brake stops due to reception of two signals.
3. Phase II guideway layout changed to take crosscoupling into consideration.
4. Merge/demerge signal phasing technique was devised for phase II to reduce 6-dB signal loss previously experienced.

h. Crossover positions:

1. Extensive efforts were made to locate and correct errors in existing crossovers.
2. Phase II utilized a new crossover technique to reduce the total number of crossovers. In addition, installation inspection procedures were improved.

i. High loop failure rate:

1. Old loops were reworked where necessary.
2. Phase II loops incorporated new installation techniques aimed at improving reliability.

4. COMMUNICATION LINK ANALYSIS

Having discussed the evolution of the Morgantown inductive communications system design it is relevant now to discuss an analytical link model that can be used to predict the operation of such a system. Throughout the design and development, extensive analysis was performed with the objective of developing a link model as a means to predict system performance. The model that will be used for our link analysis was developed in three steps. Early phase IA design data from JPL and Bendix addressed specific portions of the link and provided the framework for a link model. During the phase IB design effort, a communications study was produced that expanded on the original work and corrected certain assumptions and predictions that were found to be in error through phase IA experience. At the commencement of phase II, the communications data base study was undertaken to (1) supplement work previously done with the incorporation of phase IB experience and (2) generate a computerized link model, the data from which was used to provide phase II design requirements. The importance of this model to the ICS design warrants this summary of the results with extracts from the communication data base study.

This summary also includes, where available, the results of phase II system testing conducted at the Seattle Transportation Test Facility (STTF) and in the System Integration Laboratory (SIL) where final integration and testing of each station was undertaken. The accurate interpretation of system performance is fundamental to the developmental testing of the inductive communication system. The flow of the communication link analysis leading to the phase II design requirements is shown in figure 4-1 and keyed to the sections of this report. It is felt the information and methodology presented here will be beneficial to future system designs.

<u>Measurement Techniques and Test Methods</u>. Throughout the development of the MPRT inductive communication system, measurement methods have been continually refined by trial and error. Early developmental work and track signal evaluation and adjustment were done using a wave analyzer. Inherent in this technique were errors induced because of the complexity of the signal being measured and the wide variety of system ambient and internally generated noise and harmonics. Meter readings on the wave analyzer tended to inaccurately

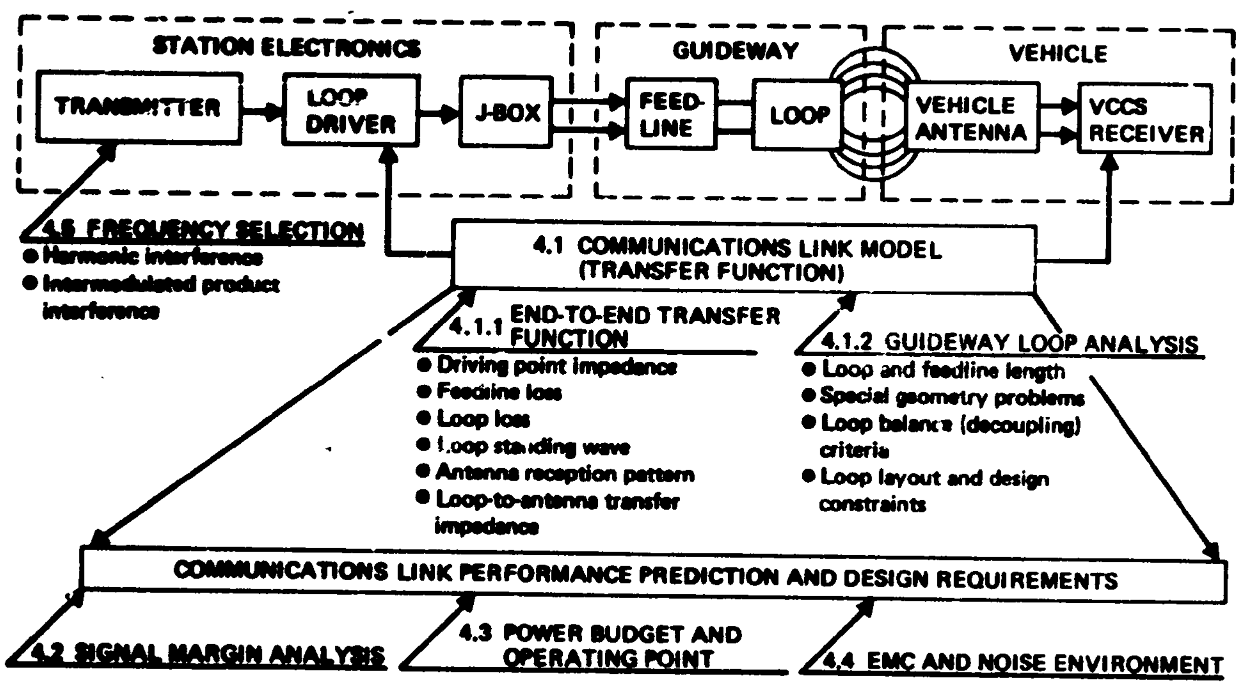


Figure 4-1. Communications Link Analysis

represent the 50 percent duty cycle of the 100 percent modulated carriers. In addition, energy from sidebands of adjacent communications signals would be summed in the meter reading along with any harmonics of lower frequency tones within the passband of the instrument. The result was apparently adequate signal levels (as measured) in a system that was actually marginal and at times not functioning as previously discussed.

Eventually accurate and extremely useful measurement techniques were developed using a low-frequency spectrum analyzer. The measurement system shown in figure 4-2 consists of a production bifilar receive antenna mounted on a portable fixture to simulate proper height and orientation. The antenna is connected to a signal conditioner that exactly duplicates the receiver front end preamplifier. The conditioner takes the differential antenna output and converts it to a single-ended signal that is fed to the spectrum analyzer at unity gain. Use of the production antenna allows evaluation of the effects of antenna offtracking and adjacent loop-to-antenna crosscoupling at merges and demerges. The spectrum analyzer display permits evaluation of potential interference within the receiver passbands, along with the capability of providing instant evaluation of distortion, through harmonic generation due to signal misadjustment. This equipment has been proved to be adequate for all phases of adjustment and developmental testing.

To satisfy system maintenance and installation and checkout requirements, procedures were developed, using the above equipment, to accurately map the guideway signal levels at periodic intervals, and to evaluate distortion on each loop. Periodic guideway surveys were initiated to ensure that the communication system was operating at optimum performance. It is felt that the next logical step is the creation of a communication evaluation vehicle that can be dispatched in the normal vehicular traffic flow. This type of vehicle would be capable of verifying system performance, daily if desired, and annunciating nonconforming areas for subsequent repair action. Such a system was not adopted at Morgantown but should be considered for any future systems.

4.1 LINK MODEL

The simplified communication link used in the development of the model is shown in figure 4-3. It includes a current driver to represent the station electronics

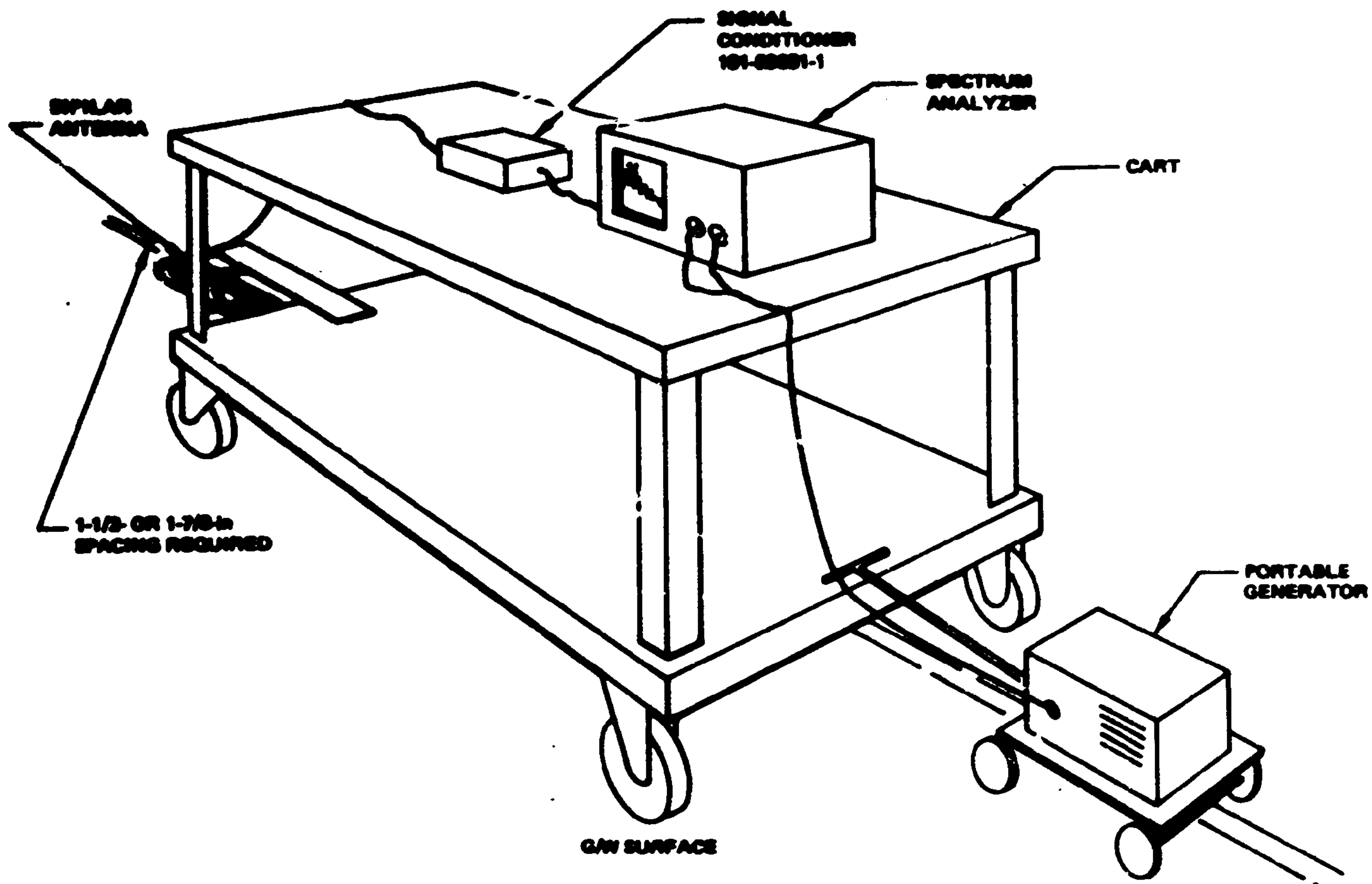
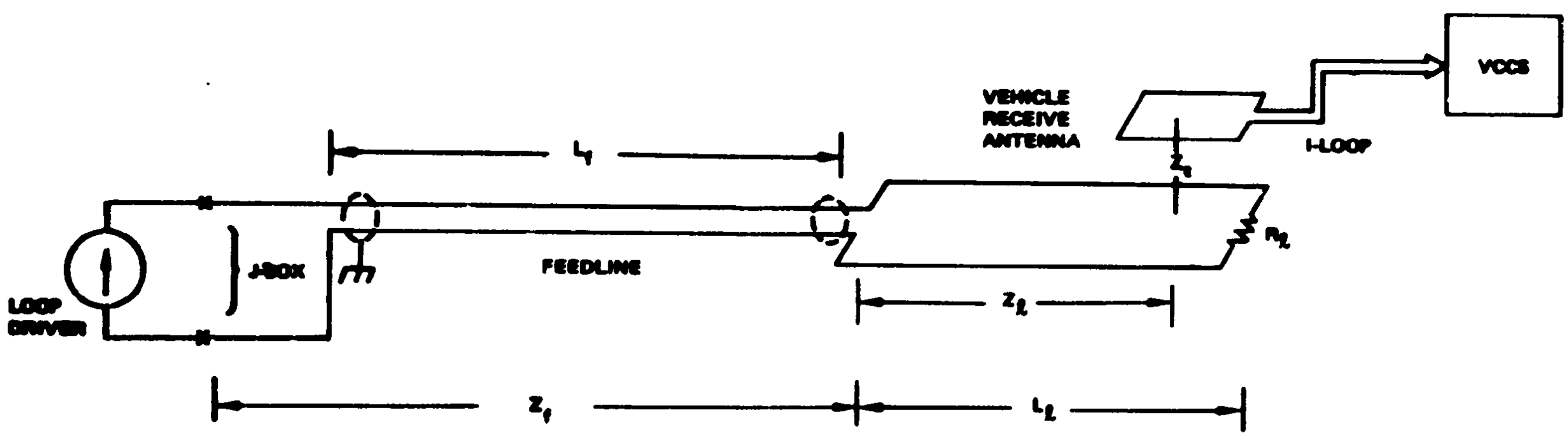


Figure 4-2. Test Setup for Spectrum Analyzer Signal Level, Leakage, and Spurious Measurements



Z_f = feedline loss (dB)
Z_ℓ = loop loss (dB)
Z_t = loop-to-antenna transfer impedance (dB) = $20 \log \frac{E_{OUT}\ (VCCS)}{I_{IN}\ (LOOP)}$

OVERALL TRANSFER IMPEDANCE $\quad Z_T = \frac{E_{OUT}}{I_{IN}}$

Figure 4-3. Link Loss Model

sources, a fixed length of feedline, a buried loop with termination to represent the guideway installations, and a vehicle antenna connected to the vehicle receiver. The purpose of this link model, as stated, was to provide a tool that will allow prediction of system performance as a function of system design parameters.

A necessary step in the evolution of a workable model is to make certain basic assumptions to narrow the scope of the task. The general assumptions made in the phase II communications data base study are listed below and are applicable to the data presented in this report.

<u>Guideway configuration:</u>

a. Guideway configuration for all signal and interface analysis is assumed to comply with phase II design requirements.
b. All loops are assumed to be Morgantown-type loops, buried in concrete, using 16-gauge wire, lying parallel to any other wires in the same slot, and separated 6 in. except at merges and demerges, which are handled as special cases.
c. Loop integrity and balance: all signal and interface analyses assume that loop isolation is maintained greater than 1 megohm above ground and that the loops are driven balanced, except for safe tone loops. It is assumed that using the phase II balance criteria provides sufficient decoupling between loops to make signal variations on loops independent of one another.

<u>Signal variations and tolerances:</u>

a. Antenna height above the loop wires is maintained to 2.36 ± 0.4 in. (±2 dB). Height is defined as shown in figure 3-23.
b. Total lateral offset of antenna centerline from loop centerline is maintained to 0.0 ± 1.5 in. (+0, -2 dB) as defined in figure 3-24, consisting of ±0.5 in. due to guideway loop installation tolerance and ±1 in. due to vehicle variations.
c. Angular antenna misalignment is assumed to be negligible.
d. Total signal variations due to all factors, except antenna height and displacement, are assumed to be 8 dB. Variations assumed for each individual frequency are smaller and stated in the signal margin calculations. Signal variations about the individual set point are unique for each

signal. Variations due to any merge or demerge are not included. Signal margins, etc., must be calculated for junctions, assuming each to be a special case.

e. It is assumed that the loop drivers are capable of supplying current to meet the nominal set point requirements.

f. Margins are calculated as shown in figure 3-30.

System configuration:

a. Bifilar receive antenna PN 191-83071-1 is mounted on the vehicle in a manner that does not perturb the reception signal pattern.

b. Transmit antenna PN 182-11530 is mounted on the vehicle in a manner that does not perturb the transmit signal pattern.

c. Phase II loop driver, FSK transmitter, and rack/drawer designs are assumed, as phase IB leakage and spurious signals would be too high to allow adjustment to specified signal levels.

d. It is assumed that system noise does not exceed the VCCS "must reject" threshold and that all noise levels are equivalent to or better than those experienced in phase IB.

In this section we discuss the development of a link model in the form of a transfer function as modified by the variable parameters within the system. The end-to-end link transfer function relates the source current supplied to the system to the voltage provided at the input to the vehicle receiver. This transfer function was developed for a system operated within defined limits and was verified through testing where warranted. The most significant variable in this model is the guideway loop configuration. Constraints were placed on the loop configurations to be used, loop and feedline lengths, loop geometry, and loop balancing. Once the configuration is defined, maximum signal variations due to guideway design parameters can be coupled with the system transfer function to permit prediction of signal margins and development of system operating points.

4.1.1 End-to-End Transfer Function

To provide the end-to-end transfer function, a simplified model was needed as a starting point. The model devised was for a typical Morgantown-type loop, buried in concrete, with the slot-to-slot differential mode parameters shown in table 4-1. The loop is fed by Belden 8720 twisted shielded-pair feedline with parameters also shown in table 4-1. As can be seen in figure 4-3 the model consists of a current driver, representing the ICS loop driver, connected at the station J-box to a feedline of length L_f, not to exceed the maximum feedline lengths shown in figure 4-4. The feedline shield is grounded to station ground at the J-box and left unterminated at the loop end. Losses along the feedline are on the order of 0.5 dB per 1000 ft for the frequencies we use and are represented by Z_f. The feedline is connected to a loop 6 in. wide consisting of #16 AWG stranded wire, buried in concrete, of length L_l, also not to exceed the maximum lengths in figure 4-4. Losses along the loop range from 2 to 3 dB per 1000 ft depending on frequency and loop configuration. The loop is terminated at its far end using a resistive load of 75 ohms. Using the program previously discussed, Z_f and Z_l can easily be determined as can the magnitude of the standing wave at the higher frequencies. Located over the loop at some place along its length is a typical bifilar receive antenna, connected to the VCCS input and terminated in the VCCS input impedance. For simplicity, in this model losses are represented as a transfer impedance in decibels relative to 1 ohm. Z_t is the transfer impedance (in decibels) between the loop and the receive antenna. It is equal to 20 times the log of the antenna output voltage (E_{out}) divided by the loop current (I_{loop}) at the feed point with respect to 1 ohm. The transfer impedance was calculated as part of the overall guideway model using a somewhat idealized mathematical model of the bifilar antenna. Since the actual antenna is wound unsymmetrically for noise rejection and to counteract metal in the vehicle, and since the actual antenna contains a forward and aft section, it was felt that there would be considerable value in verifying the calculated transfer impedance. Verification was accomplished using both mounted and unmounted bifilar antennas and checking the forward and aft sections. After compiling and analyzing all of the test and computed data, it was felt that a composite transfer impedance, reasonably accurate for all cases, could be compiled. This transfer impedance is shown in figure 4-5. These values are used for all signal-level and margin calculations unless otherwise stated.

The sum of all losses forms the overall loop driver output to VCCS input transfer impedance Z_T. Using the computer model it was possible to determine Z_T and the

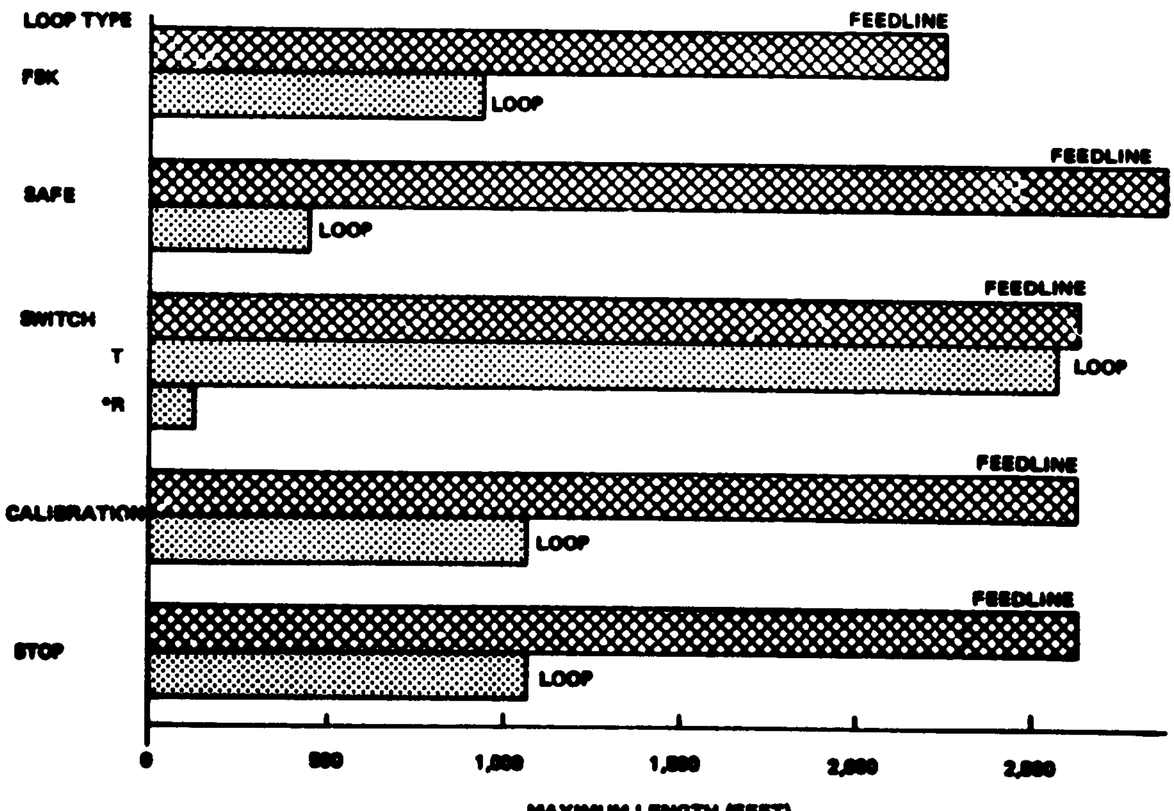
TABLE 4-1 GUIDEWAY LOOP AND FEEDLINE PARAMETERS

FREQ (kHz)	PARA-METER	SLOT-TO-SLOT DIFF. MODE	FEEDLINE (BELDEN)
6.1	Re(Z)	50.9	115.0
	Im(Z)	33.1	71.0
	Re(Γ)	.00070	.000191
	Im(Γ)	.00118	.000243
10.2	Re(Z)	80.0	104.0
	Im(Z)	40.2	54.5
	Re(Γ)	.00066	.000221
	Im(Γ)	.00131	.000421
13.3	Re(Z)	95.8	99.0
	Im(Z)	40.6	45.1
	Re(Γ)	.00064	.000257
	Im(Γ)	.00151	.000564
17.2	Re(Z)	110.	97.7
	Im(Z)	38.7	42.4
	Re(Γ)	.00062	.000318
	Im(Γ)	.00177	.000734
22.0	Re(Z)	122.	95.0
	Im(Z)	35.1	37.5
	Re(Γ)	.00061	.00037
	Im(Γ)	.00214	.00100
28.3	Re(Z)	132.	93.9
	Im(Z)	30.4	32.8
	Re(Γ)	.00061	.000436
	Im(Γ)	.00262	.001245
36.3	Re(Z)	138.	92.1
	Im(Z)	24.8	28.7
	Re(Γ)	.00060	.000501
	Im(Γ)	.00328	.001610
96.0	Re(Z)	148.	90.5
	Im(Z)	10.5	148.0
	Re(Γ)	.00059	.00089
	Im(Γ)	.00821	.0048

TABLE 4-1 GUIDEWAY LOOP AND FEEDLINE PARAMETERS (Continued)

FREQ. (kHZ)	PARA-METER	SLOT-TO-SLOT DIFF. MODE	FEEDLINE (BELDEN)
104.0	Re(z)	149.	90.0
	Im(z)	10.0	17.0
	Re(Γ)	.00059	.00085
	Im(Γ)	.00890	.0052
121.0	Re(z)	150.	89.0
	Im(z)	8.6	15.8
	Re(Γ)	.00059	.00094
	Im(Γ)	.01035	.0056
129.0	Re(z)	150.	89.3
	Im(z)	8.1	14.7
	Re(Γ)	.00059	.000970
	Im(Γ)	.01103	.005910

Loop type		Maximum feedline (ft)	Maximum loop (ft)
FSK	T	2,270	920
	R	2,270	920
Safe		2,900	430
Switch	T	2,580	2,540
	R	2,580	100
Calibration		2,580	1,080
Stop		2,580	1,080



*Based on phase IB usage.

Figure 4-4. Maximum Loop and Feedline Lengths (Phase II)

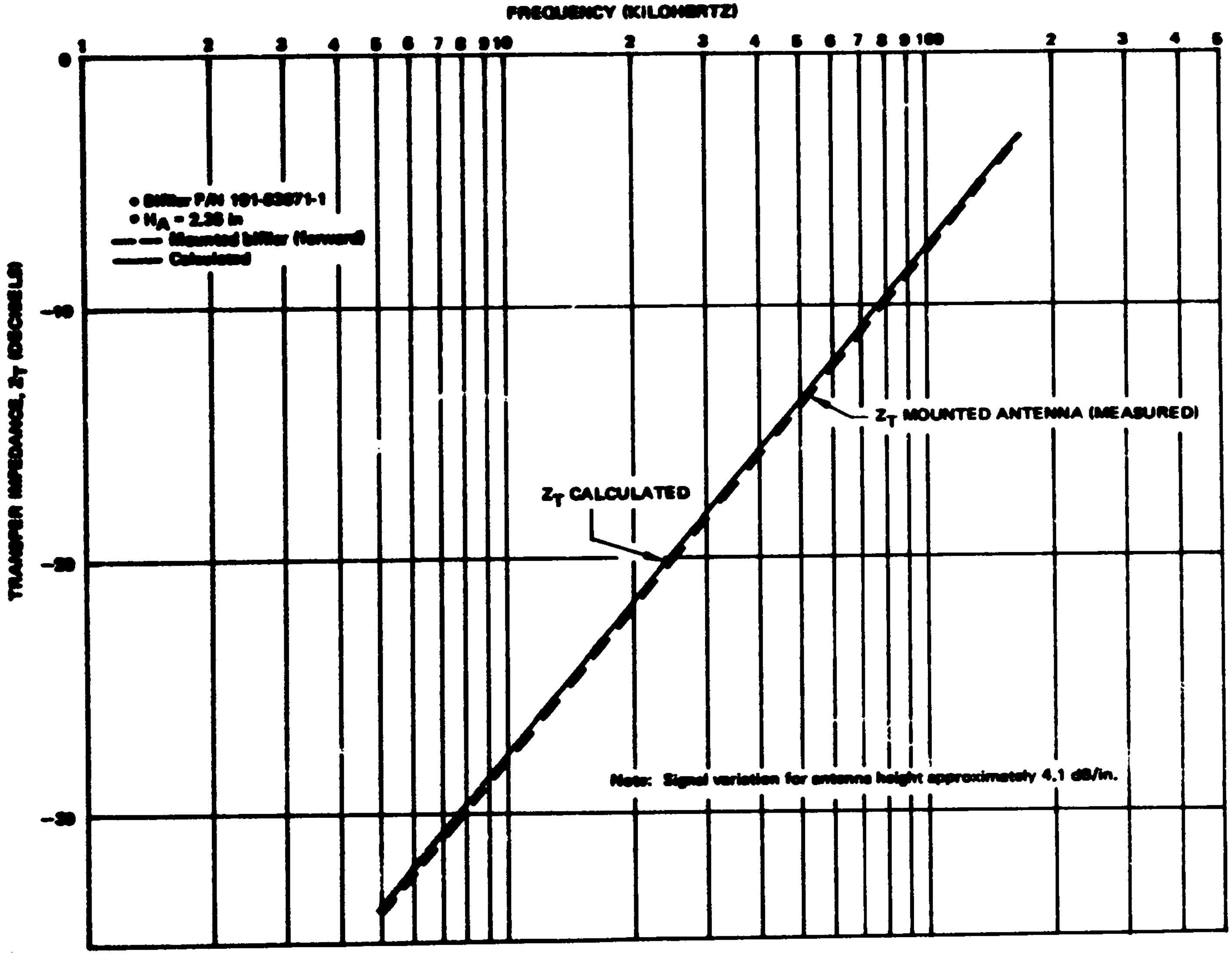


Figure 4-5. Guideway Loop to Bifilar Antenna Transfer Impedance

required input current to provide the nominal VCCS input voltage for each frequency used in the ICS system. Figures 4-6 through 4-11 show these data as a function of loop length with a fixed 3000-ft feedline length. Values of V_{out} used are the phase II nominal loop signal level set points. As can be seen from figure 4-9 a subs' .ntial standing wave was predicted at the FSK frequencies. The data from this analysis were compiled and used to derive the design parameters for the phase II ICS loop driver, in addition to providing information about loop losses and maximum end-to-end signal variations for use in margin calculations. Table 4-2 shows the overall link loss and drive requirements for the worst case phase II loop and feedline lengths. Using these data, performance requirements were derived for the phase II loop driver (fig. 4-12).

With these data as a baseline, predictions can be made for signal performance under all conditions. Two significant perturbating factors contributing to loop signal variations were singled out for further definition and verification. They are the standing waves predicted at the FSK frequencies and the antenna alignment variations experienced because of antenna tracking misalignment. To investigate end-to-end variations the loops of the phase II design were installed at the Seattle Test Track Facility and measurements were made to confirm the guideway model. A sample of 129-kHz signals measured on three loops is shown in figure 4-13; as can be seen, the standing wave is quite evident.

To study variations due to antenna position, a computer model was used to generate an antenna signal strength pattern, showing signal losses from nominal for various antenna height and lateral tracking changes. Data from this model, figure 4-14, were verified against a vehicle-mounted antenna and found to be accurate to within 1 dB.

The link model appears to give good accuracy for the simple Morgantown loops that contain no spurs and are installed properly. It should be noted that the accuracy of the computer model is only as good as the parameters from table 4-1. These parameters were estimated from several sources, one of which was the phase IB communications study. To give a further degree of confidence, measurement of the actual Morgantown parameters would be necessary. Corrections for vehicle lateral offtracking, antenna height, etc., can be made to suit any individual case

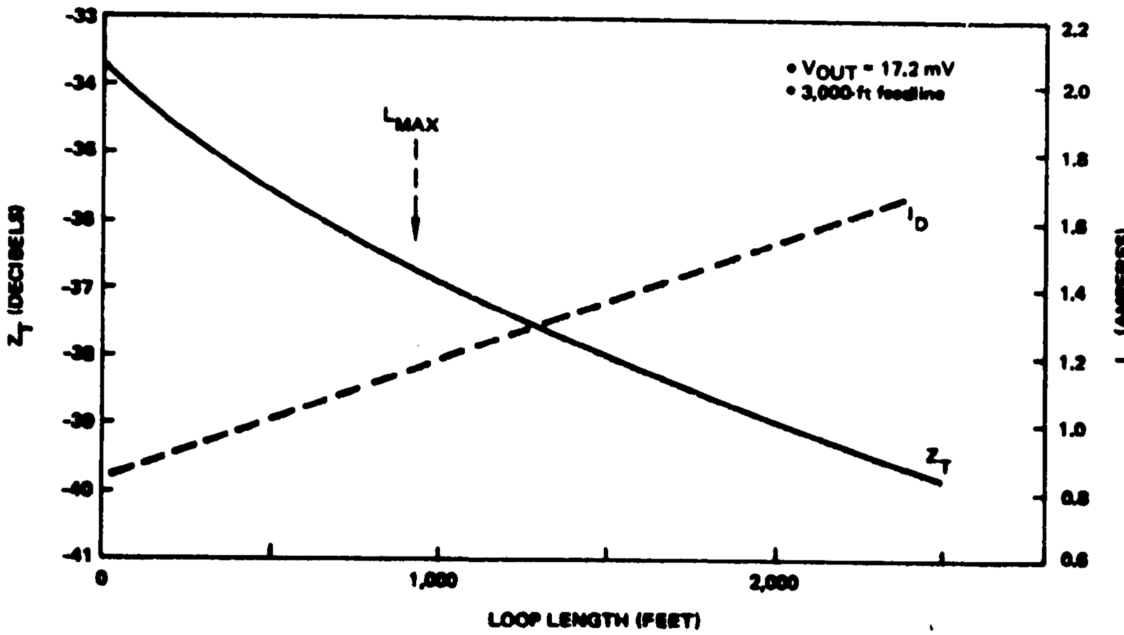


Figure 4-6. 6.1-kHz Overall Z_T and I_D

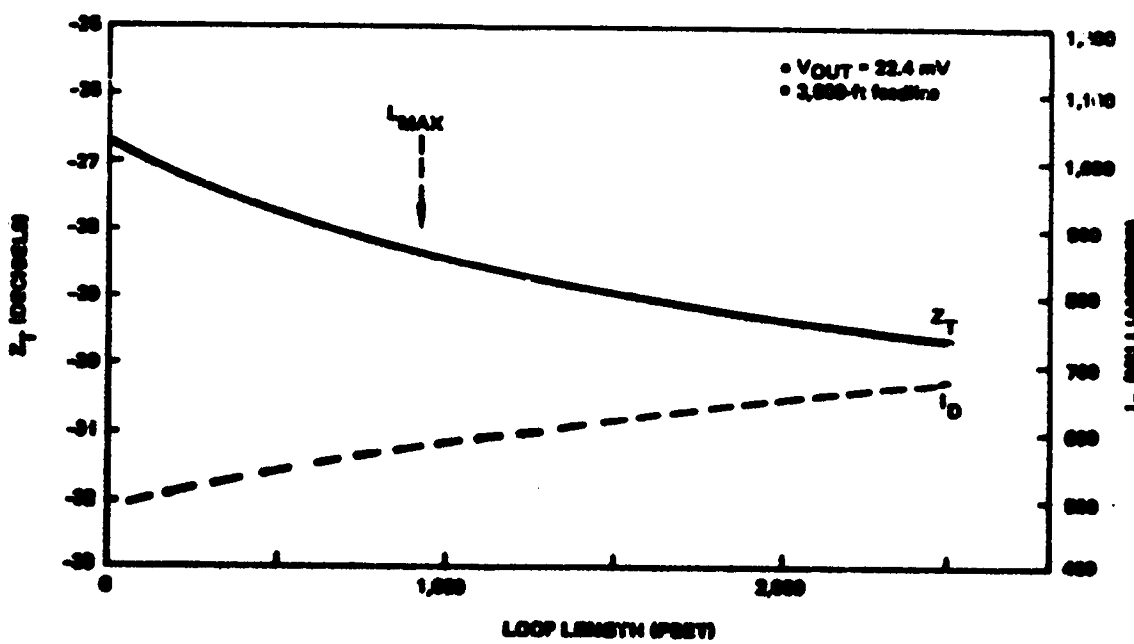


Figure 4-7. 13.3-kHz Overall Z_T and I_D

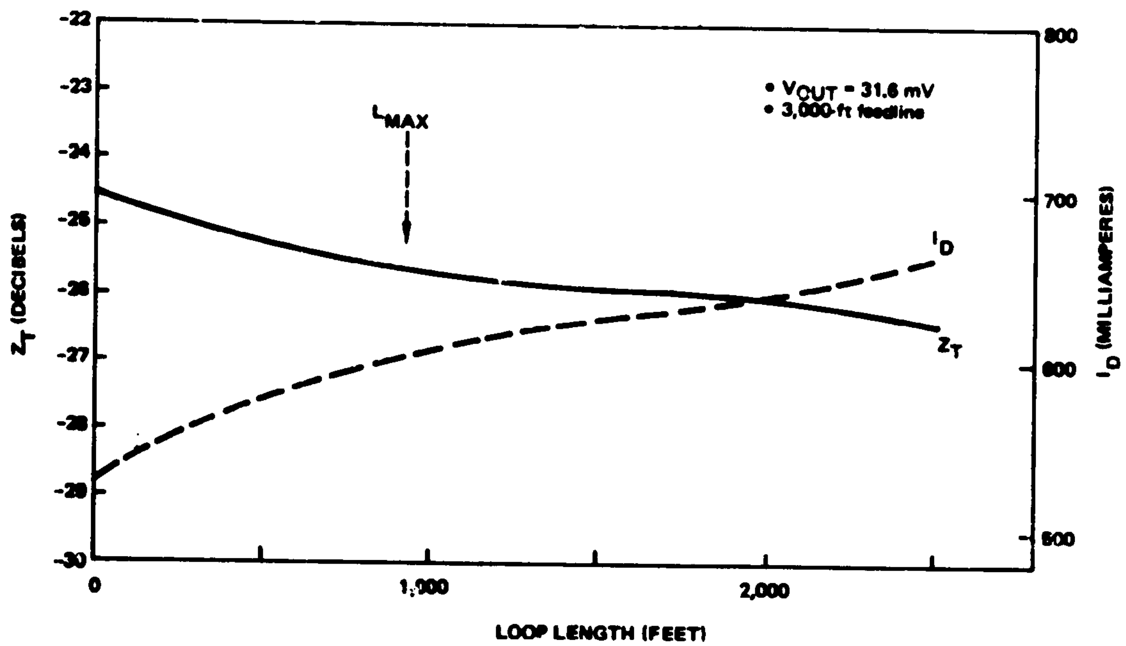


Figure 4-8. 17.2-kHz Overall Z_T and I_D

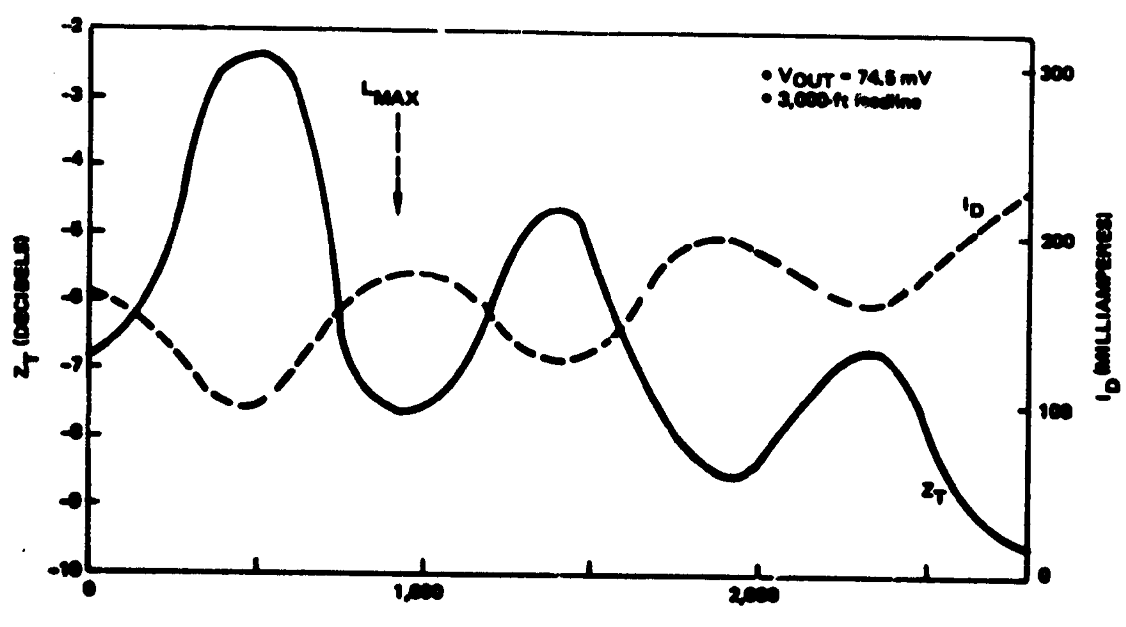


Figure 4-9. 129-kHz Overall Z_T and I_D

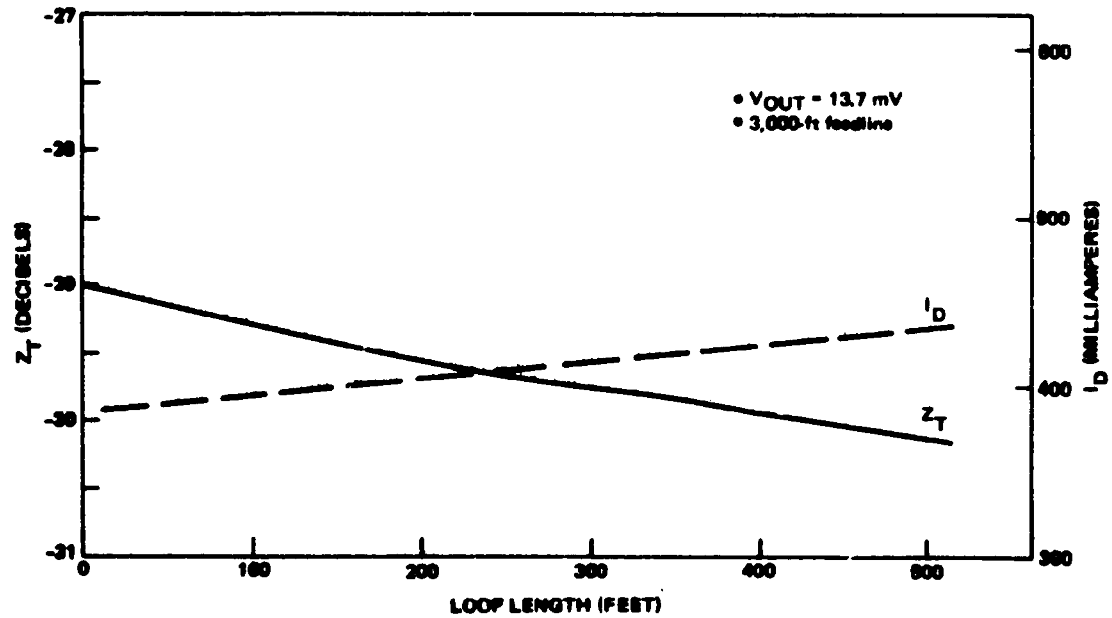


Figure 4-10. 10.2-kHz Overall Z_T and I_D

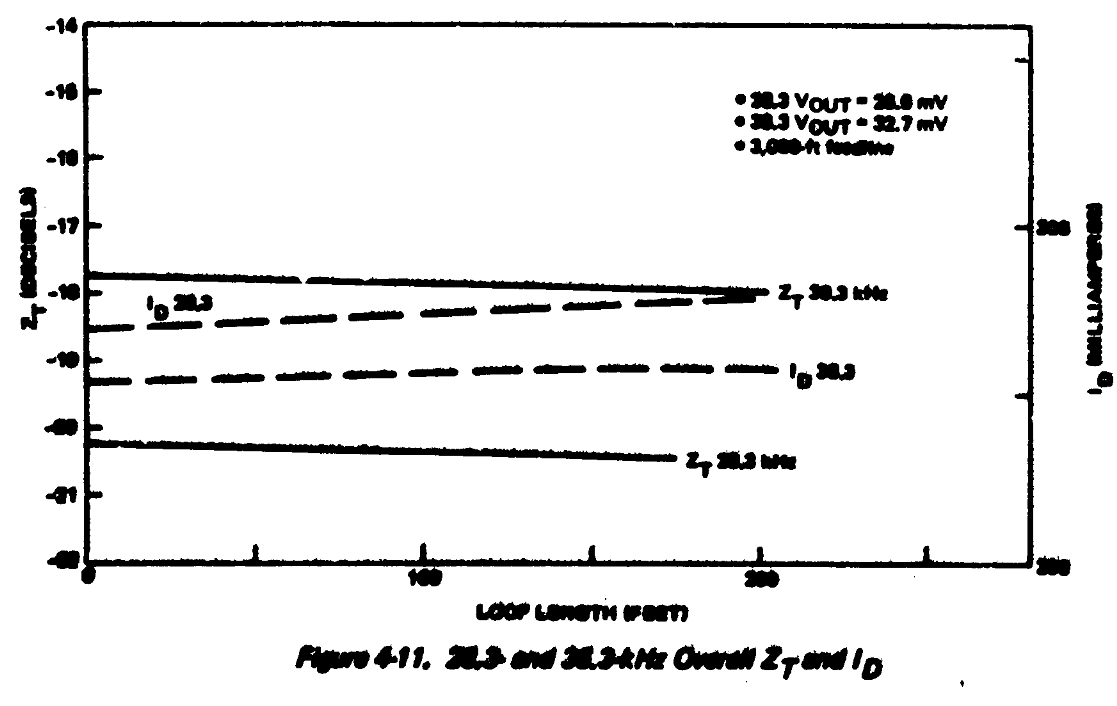


Figure 4-11. [illegible]- and [illegible]-kHz Overall Z_T and I_D

Table 4-2. Overall Link Loss and Drive Requirements

Loop type	Frequency (kHz)	Nominal set point (mV p-p)	Loop to killer Z_T (dB) [1]	Required loop current I_L (mA p-p) [3]	Maximum phase II lengths (ft): Feedline	Maximum phase II lengths (ft): Loop	Termination resistor location and value (Ω)	Loop loss (dB)	Feedline loss (dB)	Overall transfer Z Z_T (dB) [4]	I_{in} (mA p-p)	Loop driver requirements (nominal): V_L (V p-p)	Loop driver requirements (nominal): Drive Z (Ω)	Total signal variation due to loop length (dB)
PSK and speed tones	6.1	(−33.28) 17.2	31.5 −31.5	[illegible]	2,270	820	Loop end 75	2.97	0.47	−36.0	967	88.75	Re 51.75 Im 31.7	3.5
	13.3	(−33.0) 22.4	25.0 −25.0	480	2,270	820	Loop end 75	1.5	0.86	−27.4	827	46.1	Re 71.6 Im 60.4	1.5
	17.2	(−30.0) 31.6	22.5 −22.5	421	2,270	880	Loop end 75	1.15	1.0	−24.7	642	54.7	Re 84.1 Im 66.5	1.0
	121.0	(−22.8) 74.5	6.0 −6.0	148	2,270	820	Loop end 75	[2] 0.6	6.3	[2] −12.9	329	26.9	Re 80.9 Im 11.1	6.0
	128.0	(−22.8) 74.5	5.5 −5.5	140	2,270	820	Loop end 75	[2] 0.8	6.1	[2] −12.3	308	26.6	Re 84.7 Im 14.8	6.0
Safe tone (reference only)	10.2	(−37.28) 13.7	27.5 −27.5	326	2,900	430	Feedline 60	0.1	0.9	−28.3	357	28.4	Re 61.8 Im 48.8	1.0
Switch tone	28.3	(−31.0) 26.6	18.5 −18.5	224	2,880	200	Feedline 75	0.1	2.0	−20.3	278	28.1	Re 91.4 Im 44.7	1.0
Calibration/ step tones	38.3	(−29.7) 32.7	16.0 −16.0	286	2,880	200	Feedline 75	0.1	2.3	−18.1	283	27.8	Re 90.3 Im 33.4	1.0

[1] Decibels relative to 1Ω.

[2] Figures shown are for maximum loss point, which is not at loop end.

[3] $I = V \times 10^{-(Z_T/20)}$

[4] $Z_T = 20 \log \frac{E_{OUT}\ (VCCS)}{E_{IN}\ (Loop)}$

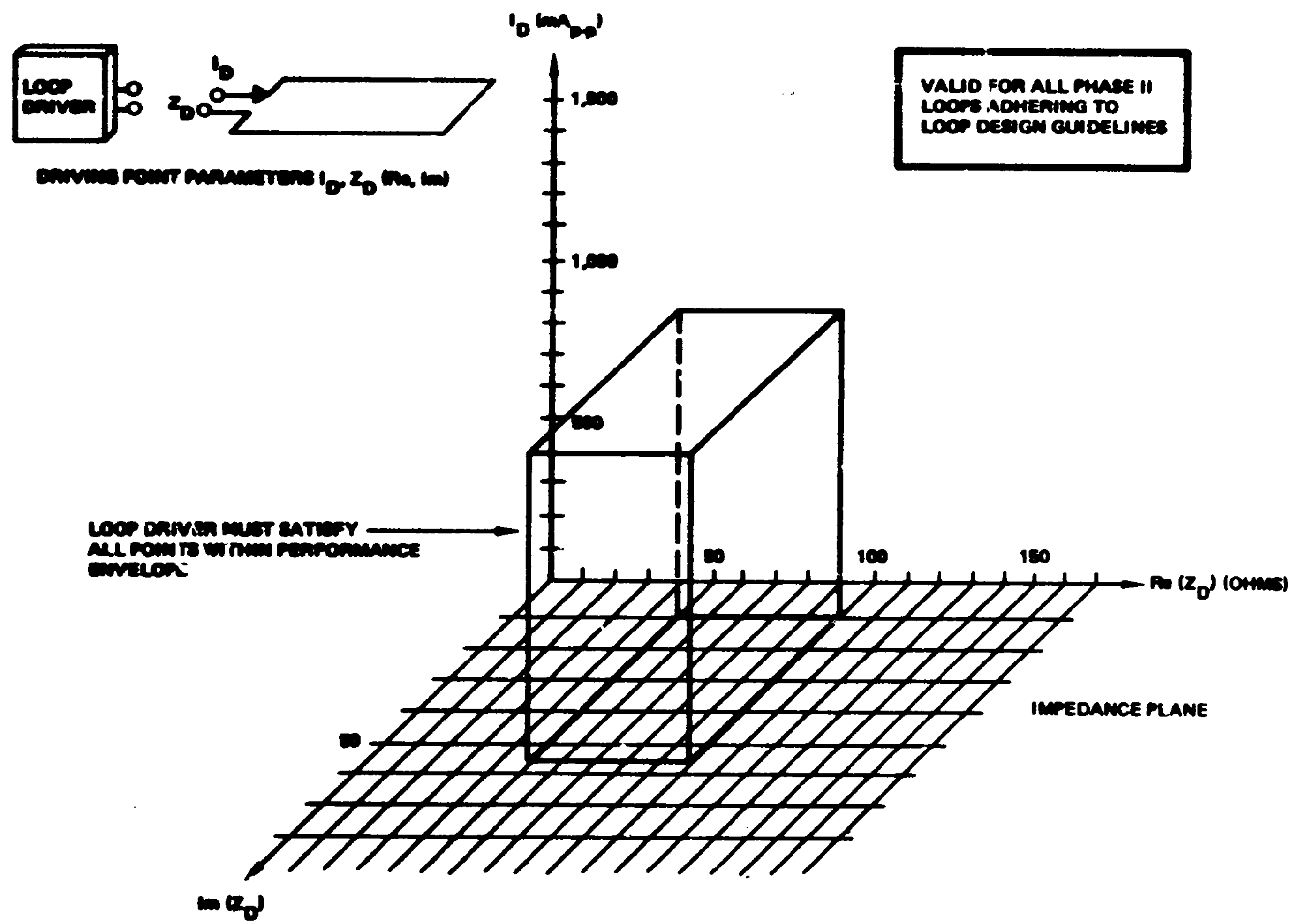
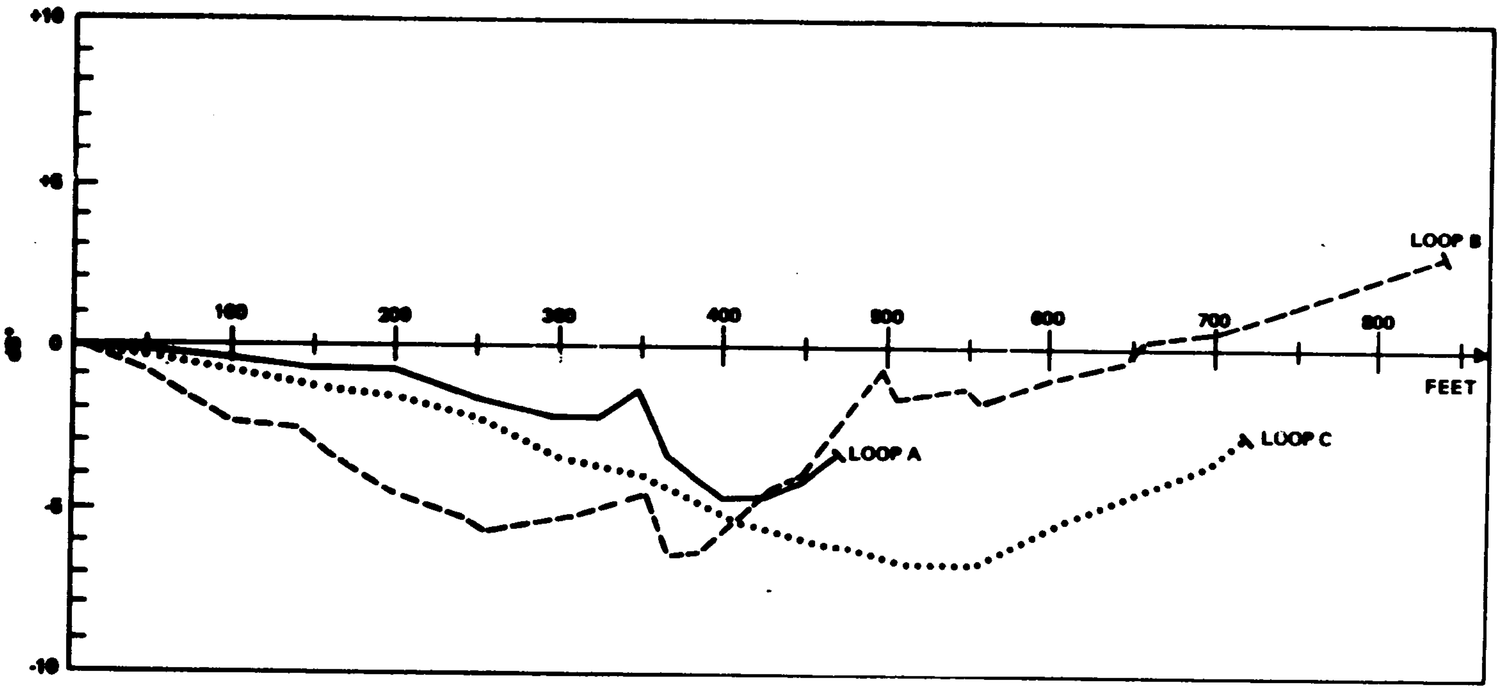


Figure 4-12. Loop Driver Performance Envelope



*Referenced to signal at feedpoint.

Figure 4-13. Measured Loop Signal as a Function of Distance From Feedpoint for 121-kHz at STTF

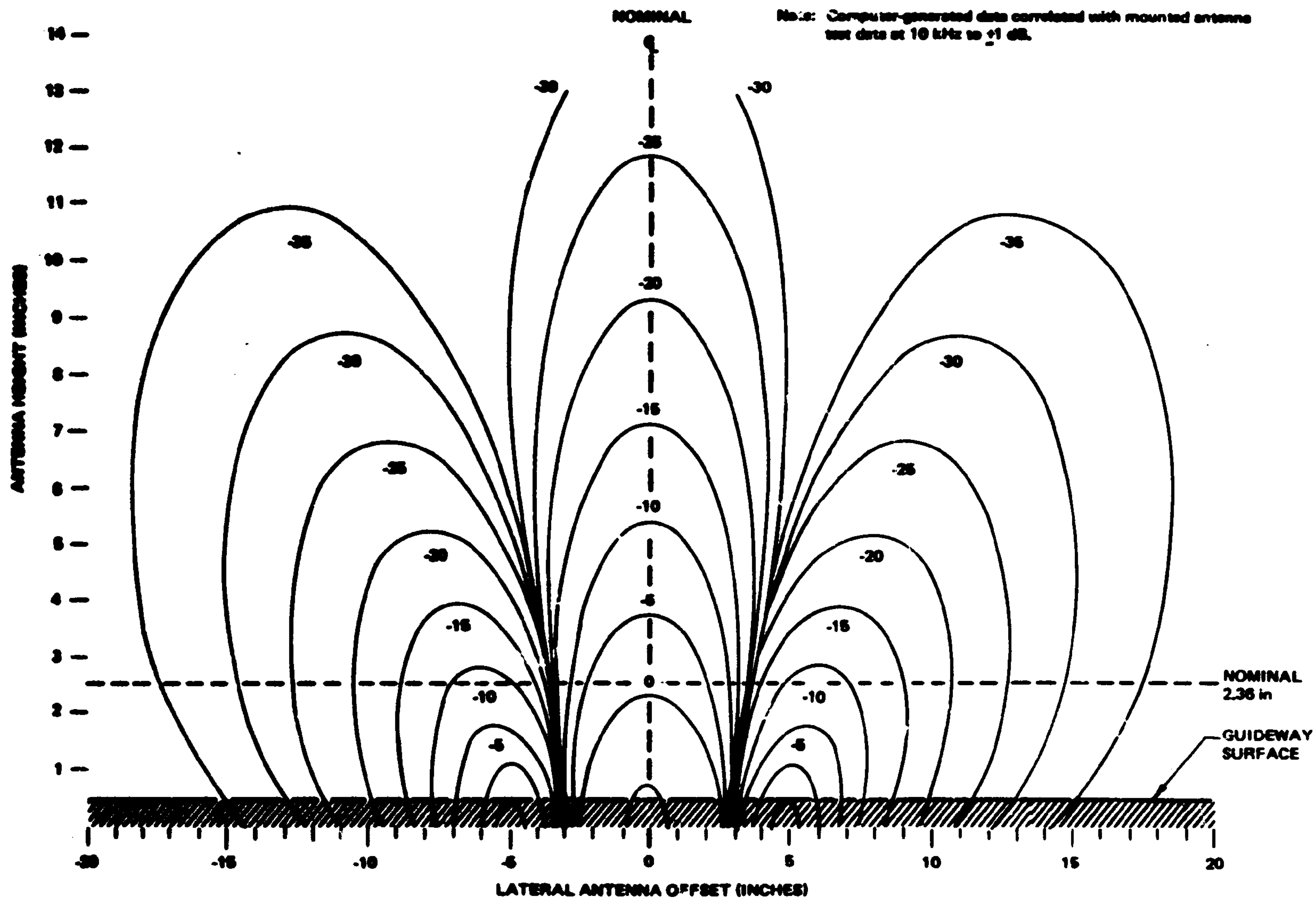


Figure 4-14. Signal Strength Pattern—6-in Loop and Bifilar Antenna

using the data presented. A comparison of the model data against field measurements made during phase IB I&CO yields a high degree of correlation, with any errors being on the conservative side.

4.1.2 Guideway Loop Analysis

A guideway loop subsystem analysis was conducted to establish variations that could be applied to the transfer function model and to permit evolution of the "typical" loop model, thus enabling performance to be predicted for all cases of the real system. This analysis generated data on signal variations as a function of loop configuration and conversely was used to establish loop design guidelines to ensure that system performance goals would be met. The analysis has been broken into four subjects: loop and feedline length constraints, loop layout constraints, merge/demerge junction layout, and loop balance criteria (or loop-to-loop decoupling).

Loop and Feedline Length. For the most part, maximum loop and feedline lengths are arrived at as a function of guideway layout with consideration given to drive impedance, end-to-end signal variation, current drive requirements, and overall system transfer impedance, to ensure the loops are within the design capabilities of the station electronics. As shown previously, the computer model was used to analyze the effects of length on signal level. Using the preliminary signal margin calculations, the maximum desirable signal variation was determined and then applied to the data to obtain the maximum loop and feedline lengths that would meet those criteria.

In general, if feedline lengths are kept significantly less than 1/4 wavelength, they can be assumed to represent a linear loss/unit length of about 0.5 dB/1,000 ft. Based on these data and assuming a 1.5-dB feedline loss could be compensated for through signal adjustment, the maximum length was selected to be 3,000 ft. Overall loop length was constrained to meet end-to-end signal variation and drive requirement goals. However, for the most part, lengths were not critical in loops with no spurs except for FSK loops where the loop length approached 1/4 wavelength. As can be seen, the major factor affecting overall loop length is the degree of mismatch permitted between the loop driver and feedline, the feedline and the loop, and the loop and its termination resistor. Ideally the loop characteristic impedance should be determined for a given case and the feedline, loop driver output, and termination matched to it. If this were done, even the high-frequency FSK loops could be several thousand feet long and suffer only a uniform loss per unit length. Two factors made this optimum approach impractical for Morgantown: (1) a feedline of the same characteristic impedance as the loop was not commercially available and (2) the Morgantown system layout does not require loops or feedlines in excess of those achievable with tolerable mismatch. The cost of further improvement therefore was not justified.

Loop Layout and Design Constraints. A set of loop layout and design constraints was developed for the phase II system design using the modeling techniques previously discussed along with commonsense rules derived from experience and analysis. The constraints are as follows:

a. The loop feed location shall always be at the end of the longest segment (a result of treating the loop as a transmission line).

b. In the case where termination resistors are installed at the loop end, they shall be installed at the opposite end from the feedpoint of the longest segment.

c. In all cases, loop leadouts to the cable tray shall be twisted a minimum of six turns per foot. (This is to reduce coupling to and from other leadouts installed in the same slot and coupling from the adjacent power rails.)

d. Loops may not be split into two sections and driven in series through a connecting feedline, with the exception of safe tone loops under 200 ft in length. (This results from experience in the phase IB system where it was found that capacitance of the feedline at the frequencies used caused most of the current to circulate in the first loop, and very little in the second, a situation that cannot be compensated for through adjustment.)

e. Spurs or stubs are permitted up to a maximum of three per loop as long as the maximum length of any spur does not exceed 100 ft. (Again, rules for transmission lines seen to apply at the higher frequencies.)

f. No splices shall be located in the buried loops. (Splices were the single highest contributor to loop failures.)

g. Termination resistors shall be located in the cable trays adjacent to the guideway (a reliability consideration, to place the resistor in a less hostile environment).

h. For all loops with frequencies of 36.3 kHz and lower, the termination resistor may be split into two equal halves and located at the feedline end of the loop. For FSK/speed tone loops, the resistor must still be located at the loop end. (This was a concession to reduce loop installation costs.)

i. All loops shall be crossed over in one leg of a merge or demerge to reduce signal degradation (causes crosscoupled currents in antenna to become additive).

j. For large-radius merges and demerges (greater than 1000 ft), the alternative junction geometry must be implemented (as discussed next).

It is our experience that following the above rules will provide the most reliable guideway loop system possible, with the least signal degradation and end-to-end variation.

Merge/Demerge Geometry. Because of the close proximity of loop segments at merges and demerges, a significant signal degradation was found to occur that is ouside the allowable tolerance. The problem is manifested in two ways.

The first is crosscoupling of noncompatible or undesired signals that occur in areas where the two branches of a junction contain different loops, as shown in figure 4-15. The second is a simple loss of signal strength caused by cancellation of signals from the two segments when they are both from the same loop because of out-of-phase currents being induced in the antenna (fig. 4-16). The first problem can only be corrected by extending the loop end to a point where the loops are separated by at least 18 in. The second—that of out-of-phase signal cancellation—can be modified by changes in loop geometry. Figure 4-17 shows the signal loss

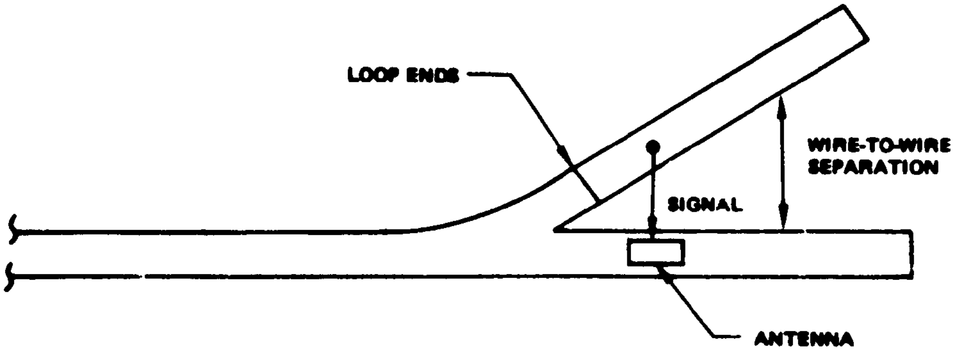


Figure 4-15. Loop Crosscoupling

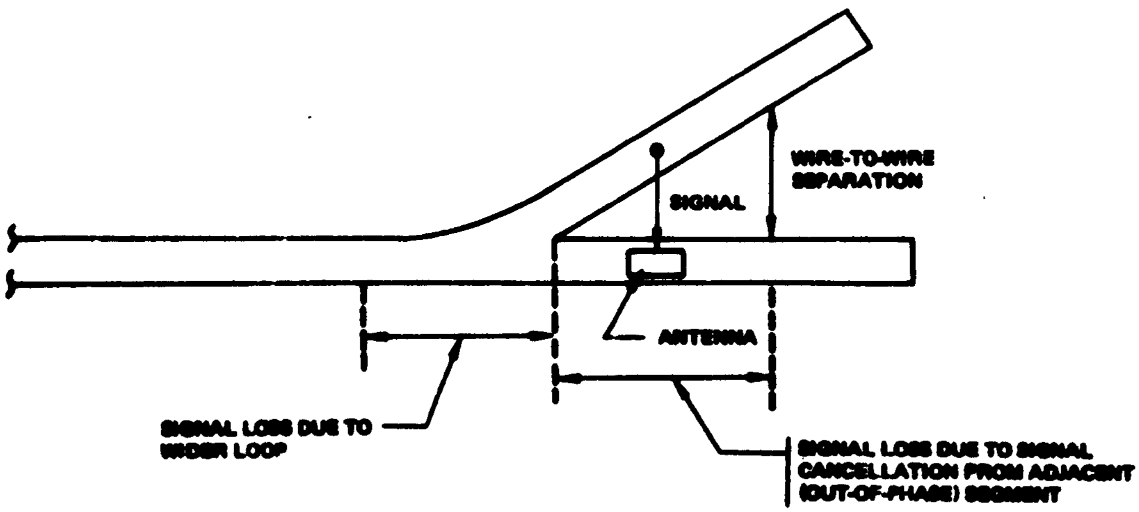


Figure 4-16. Merge/Demerge Signal Degradation

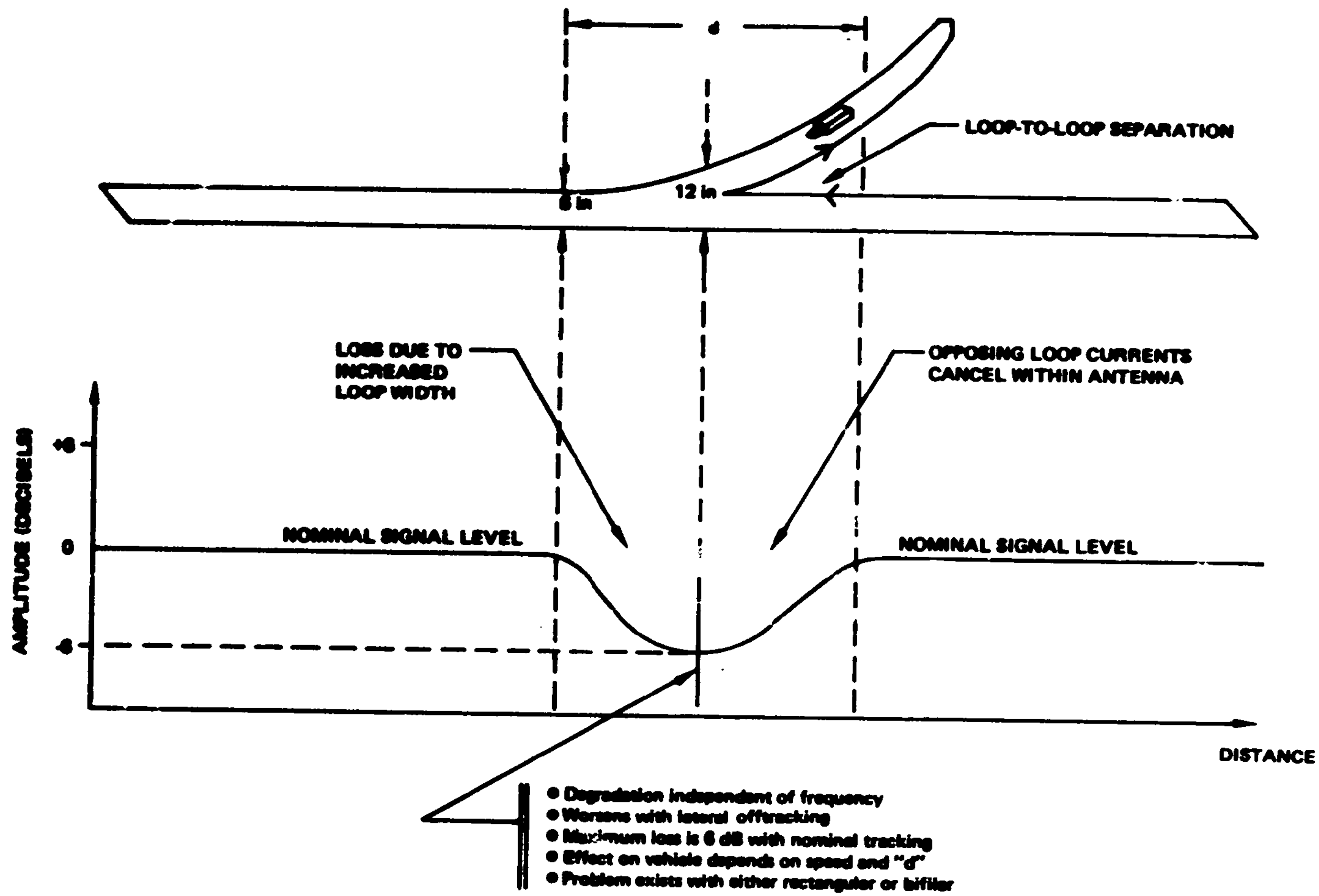


Figure 4-17. Basic Merge/Demerge Configuration

experienced when going through a junction. The effects of this loss on system performance are proportional to the radius of the demerge and vehicle speed since those parameters determine the length of time the VCCS sees the low signal level. Two geometry changes have been incorporated into the phase II system design to correct this problem. The first (fig. 4-18), used at less critical areas, is the simple addition of a crossover to bring the signals from each junction half into an additive situation within the antenna thus causing a short period of signal degradation as the loop widens from 6 in. to the 12 in. required to split, and a period of boosted signal strength as the antenna "sees" two signal sources in phase. The second is a "special" junction configuration used at large-radius demerges where even the degradation from the increased loop width occurs over such a long period of time as to become detrimental. This method reduces the magnitude and duration of the dropout and involves modifying the actual installation geometry in addition to adding a crossover. Here, the frog and crossover are extended back to a point where the loop width is only 10 in., thus resulting in only a 3.5-dB signal loss, as shown in figure 4-19. Careful consideration of loop geometry is recommended in the initial system design for any new systems to minimize the need for corrective action to preserve signal integrity.

Loop Balance Criteria. The objective of loop balancing is to decouple overlying and underlying loops each from the other to ensure that signals are not detected past loop ends. Analysis of the loop-to-loop interaction at the frequencies we use reveals that the loops are loosely coupled even though they run parallel in the same slots for many hundreds of feet. Figure 4-20 shows that if no decoupling were attempted, up to 70 dB of natural isolation (transfer ratio of current into primary loop versus antenna output voltage over second loop) would exist at the lower frequencies. A line has been drawn on the plot to show the minimum required isolation to meet spurious signal specifications. As we can see, this specification could possibly be met at the lower frequencies with no decoupling whatsoever. To ensure the loops are decoupled at all frequencies and to provide some margin for loop variations, a technique was devised using phase reversals or crossovers to decouple each loop from every other loop. The methods used are discussed in section 3.2.2.2 and are shown in figures 3-21 and 3-22. Analysis using the system model has shown that an additional decoupling of from 20 to 50 dB can be achieved with the addition of these crossovers, as shown in figure 4-20. The limiting

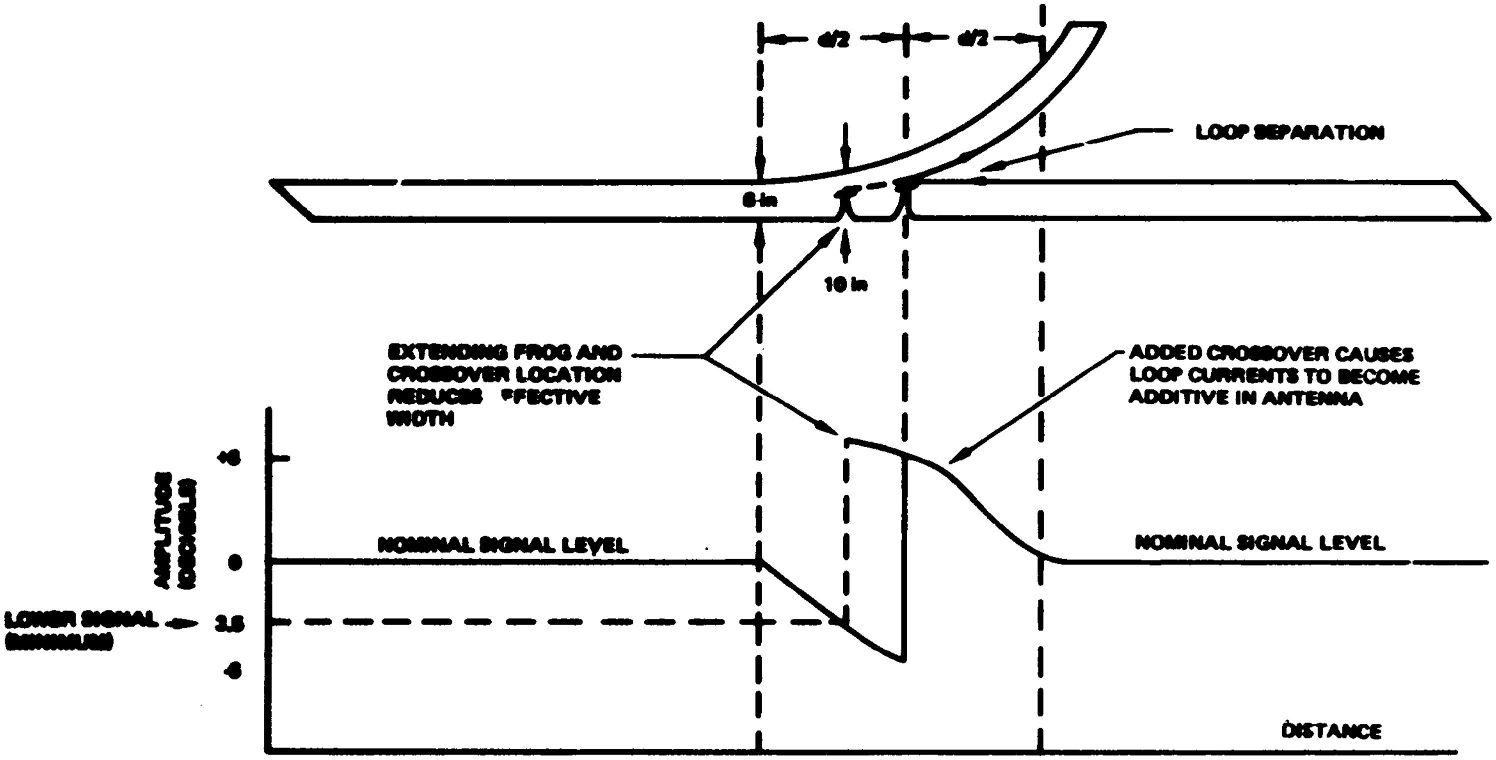
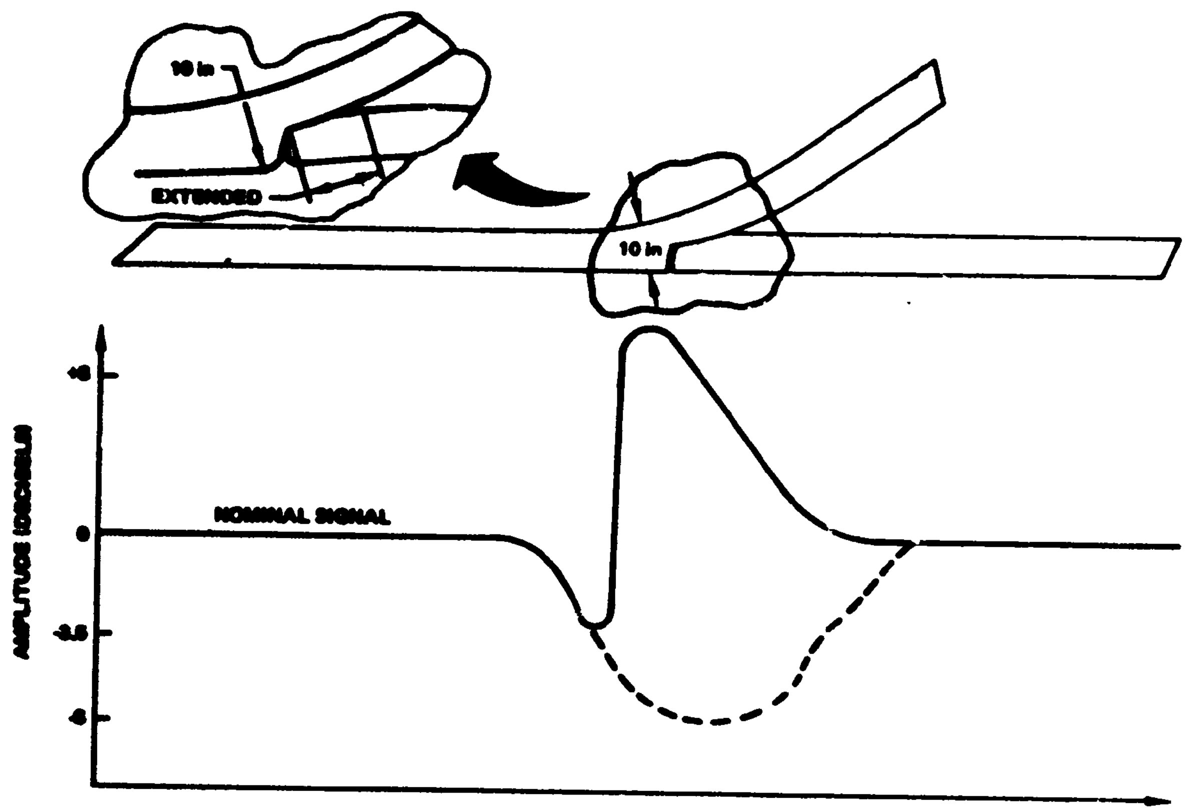


Figure 4-18. Modified Junction, Crossover, and Extension



- Reduces magnitude of signal loss
- Workable for up to ±1 in lateral antenna effect
- Maximum loop width 10 in

Figure 4-19. Modified Junction — Expanded Detail

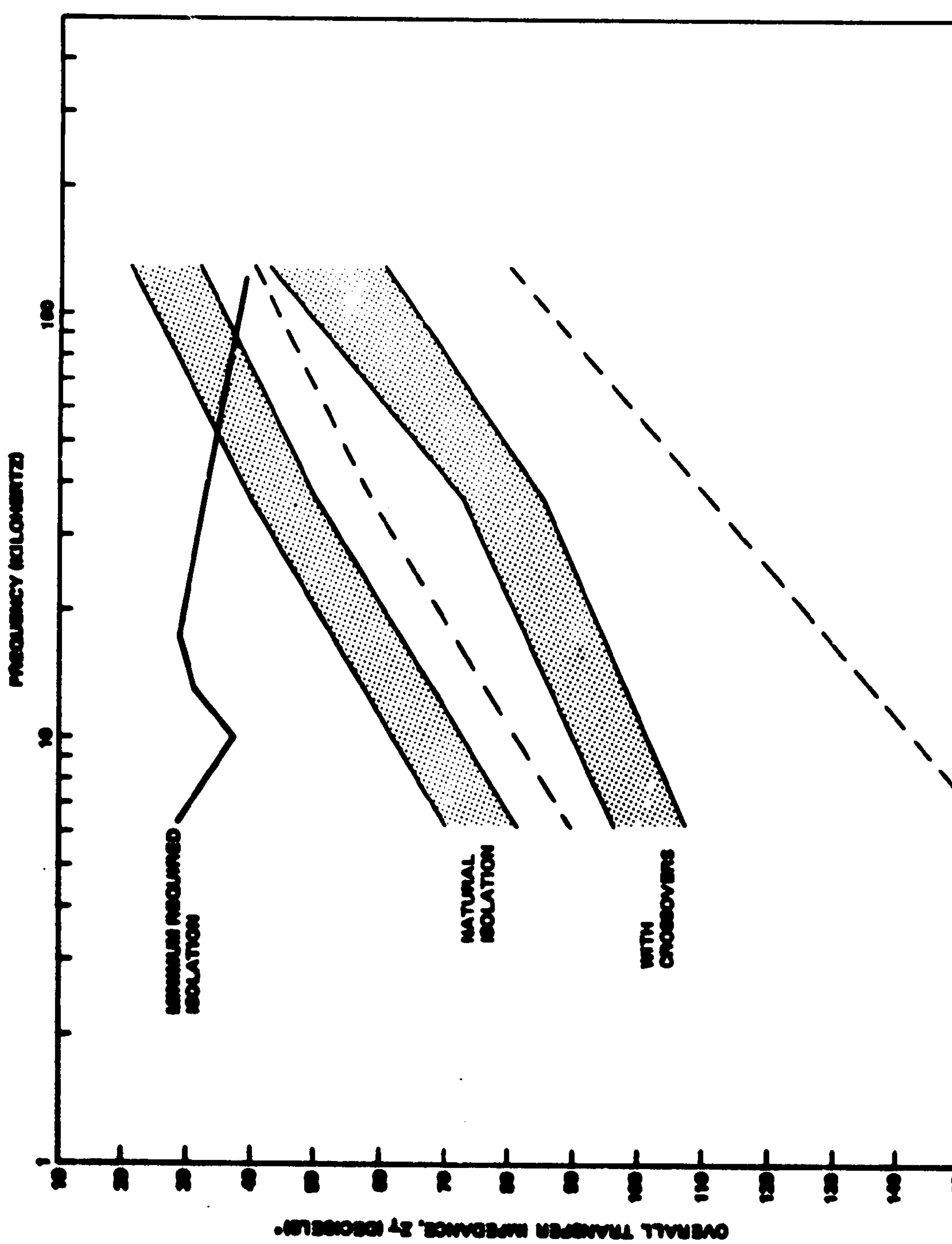


Figure 4-20. Loop Isolation Versus Frequency

*Coupled through isolated loop.

factors, especially at the higher frequencies, appear to be the uncertainty of loop-to-loop coupling within the slots as wires assume various positions with respect to each other, and the effects of standing wave and phase shift with distance on the ability to approach the 180-deg phase difference and equal magnitude currents needed for complete cancellation of the unwanted signal. Table 4-3 shows the loop isolations obtained and the margin calculated for the phase II guideway. A new balancing criterion was devised for phase II, which balanced larger segments of the guideway simultaneously thus achieving a reduction in the number of crossovers and related system installation costs. This criterion was implemented in a computer program that along with supplying tables of crossover locations also provided maps (via a plotter) of the loops and their crossover locations similar to the one shown in figure 4-21.

4.2 SIGNAL MARGIN ANALYSIS

The transfer function and associated variations developed using the link model provide the tools necessary to perform a signal margin analysis, one step in developing system design requirements. The following margin analysis was done for the phase II system. It couples signal levels predicted using the transfer function with all variables expected in real system operation. The margin calculations are made for the phase II system design assuming that no equipment anomalies (e.g., leakage, spurious signals, harmonics, or insufficient drive) are present to prevent adjustment to the optimum operating points.

Figure 4-22 summarizes the results of the margin calculations for all uplink frequencies in the phase II system. It should be noted that for the 10.2-kHz safe tone frequency no change has been made from the phase IB design; therefore, actual operating points are shown as derived from I&CO data. For all frequencies except 121 and 129 kHz, the loop end-to-end signal variation has been held to less than 4 dB and in most cases less than 1 dB. For the longest FSK loop, the predicted variation is just over 5 dB. End-to-end loop signal variation is dependent on guideway configuration, particularly the number of spurs in the loop and the length of the loop and spurs. The variation is also dependent on frequency; the shorter, lower frequency loops exhibit a semilinear signal loss of about 2 to 3 dB per 1000 ft, while the higher frequency FSK loops begin to show signs of standing wave

TABLE 4-3 LOOP ISOLATION MARGIN

	FREQUENCY kHz	TYPICAL ISOLATION (dB)	WORST-CASE SIGNAL (mVp-p)	MAXIMUM PERMITTED SIGNAL (mVp-p)	ISOLATION MARGIN [1] (dB)
FSK LOOP	6.1	100	.0003	.5	64
	13.3	85	.0022	.5	47
	17.2	80	.0056	1.0	45
	121 & 129*	44	1.6	2.0	2
SAFE TONE LOOP	10.2	88	.00135	.25	45
SWITCH LOOP	28.3	76	.008	1.5	45
CAL/STOP LOOP	36.3	70	.019	1.3	36

* ISOLATION NOT CRITICAL

[1] ISOLATION MARGIN MEASURED BETWEEN VCCS MUST REJECT AND ACTUAL ISOLATION

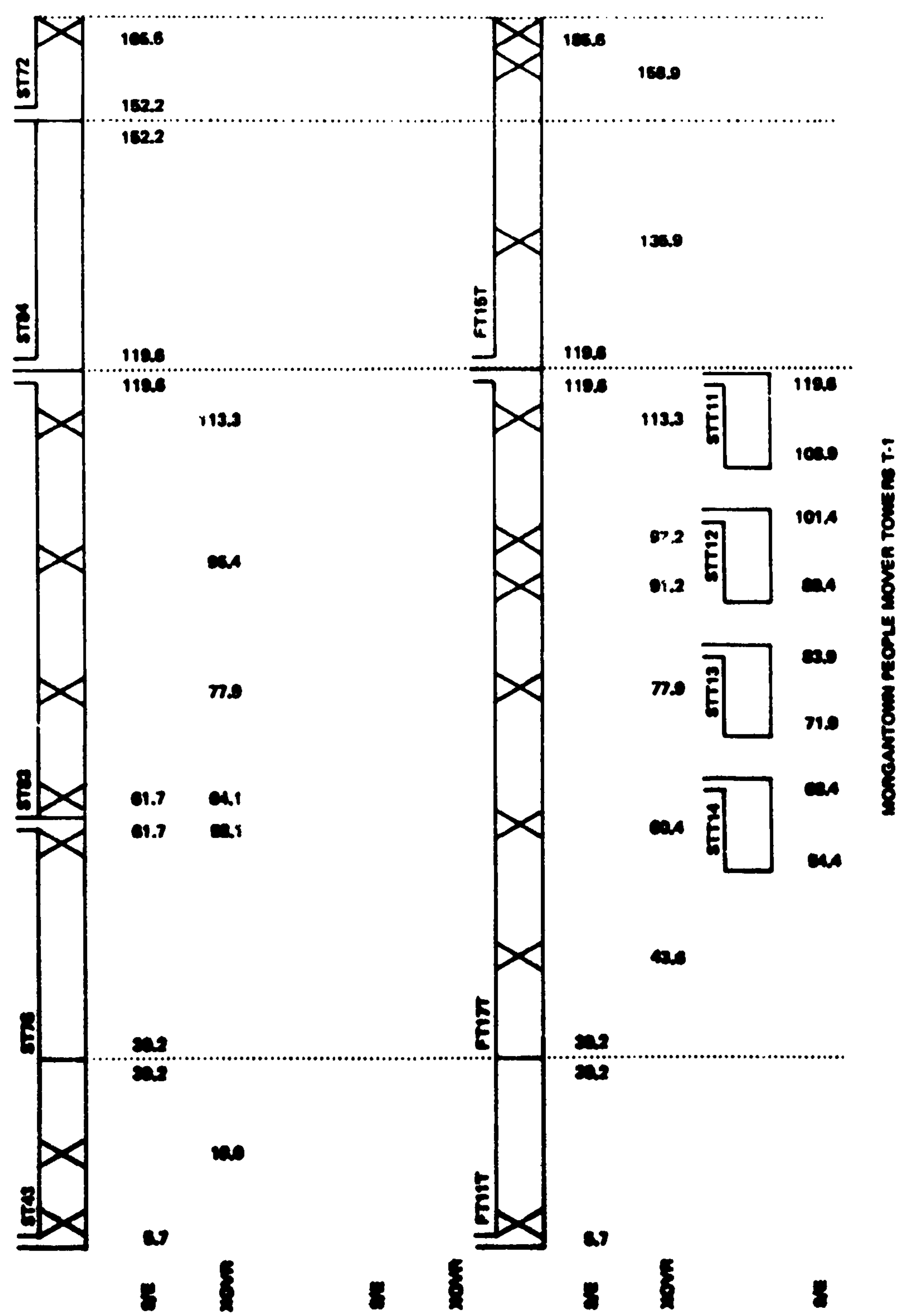


Figure 4-21. Crossover Program Typical Output

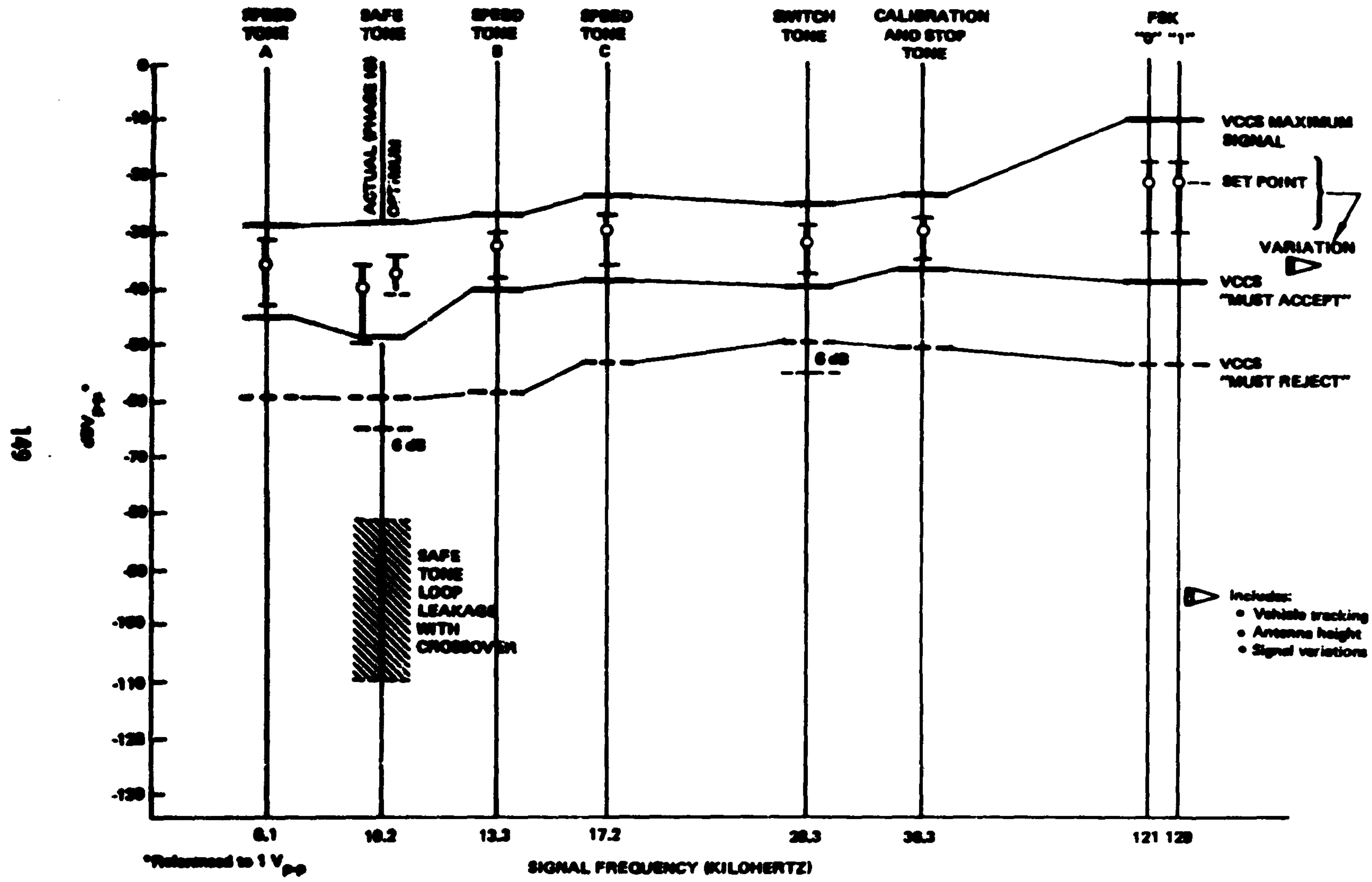


Figure 4-22. Uplink Signal Margins—Phase II

effects that, if the loop were long enough, would result in up to a 14-dB variation end to end. The overall variations shown in figure 4-22 consist of loop signal variations and variations due to external vehicle-related effects. Figures 4-23 through 4-25 show in detail the margin calculations for the three-speed tones.

The 6.1-kHz plot (fig. 4-23) shows that the nominal signal "set point" is located at the upper end of the signal variation tolerance. This allows for greater variations in the negative direction, since signal loss and resulting downtime are most likely to occur from a lack of signal. Another reason for locating the set point at either the signal maximum or the signal minimum comes from the practical task of adjusting the signals on the guideway. A quick signal mapping of the quideway loop to be adjusted will easily locate the signal maximum and minimum points and confirm that the overall variation is not greater than permitted. It would be more complex to require the signal to be adjusted at the average point because that would be somewhat difficult to locate. Since the set point in the margin calculation is at the signal variation maximum, this will require the loop adjustment to be made using test equipment located at the loop maximum signal point. Alternative adjustment procedures are provided to center the adjustment when the loop signal variation exceeds the allotted maximum. Margin determination and signal level adjustment are similar for all other frequencies used, with particular attention paid to variations due to standing waves at the FSK frequencies.

As part of the analysis to determine effects of vehicle tracking variations on signal reception, a plot was made at the safe tone frequency with VCCS thresholds superimposed on the bifilar antenna reception pattern (fig. 4-26). The crosshatch areas, flagnote 1, are the guaranteed performance range—that area where the signal will remain above the VCCS "must accept" threshold. The light grey area, flagnote 2, prescribes the "must reject" threshold, beyond which the VCCS will not detect a valid signal. Much of the apparent random performance of the phase IA and early phase IB systems can be accounted for by observing the very large questionable area where individual VCCS's and vehicles might or might not detect a valid signal. These data become particularly significant when discussing vehicle offtracking or merge/demerge crosscoupling problems.

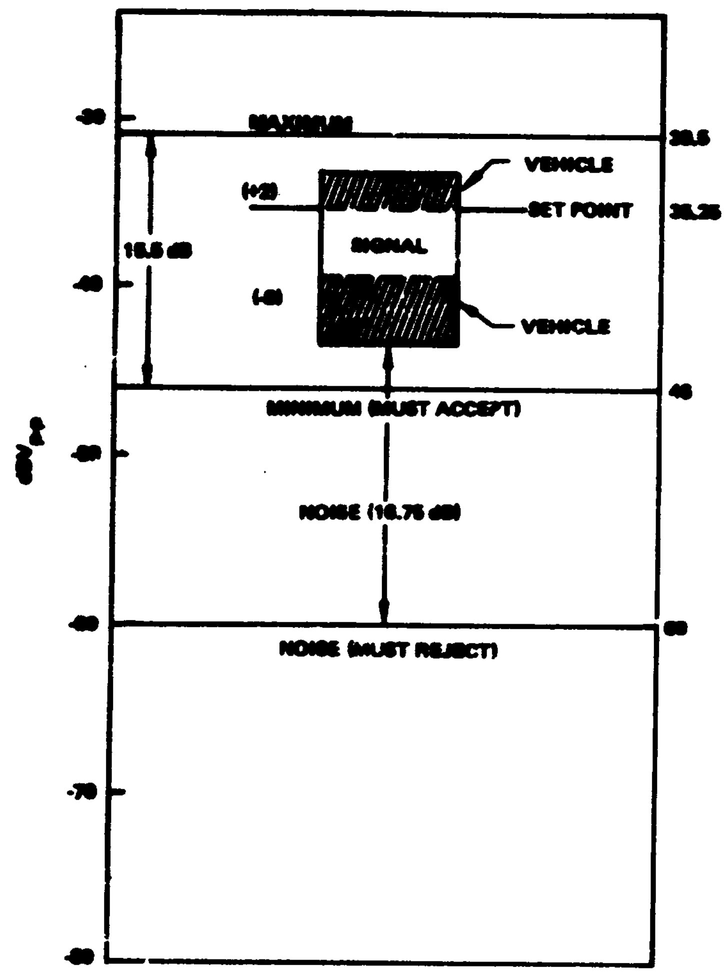


Figure 4-23. 6.1-kHz Signal Margin—Speed Tone A

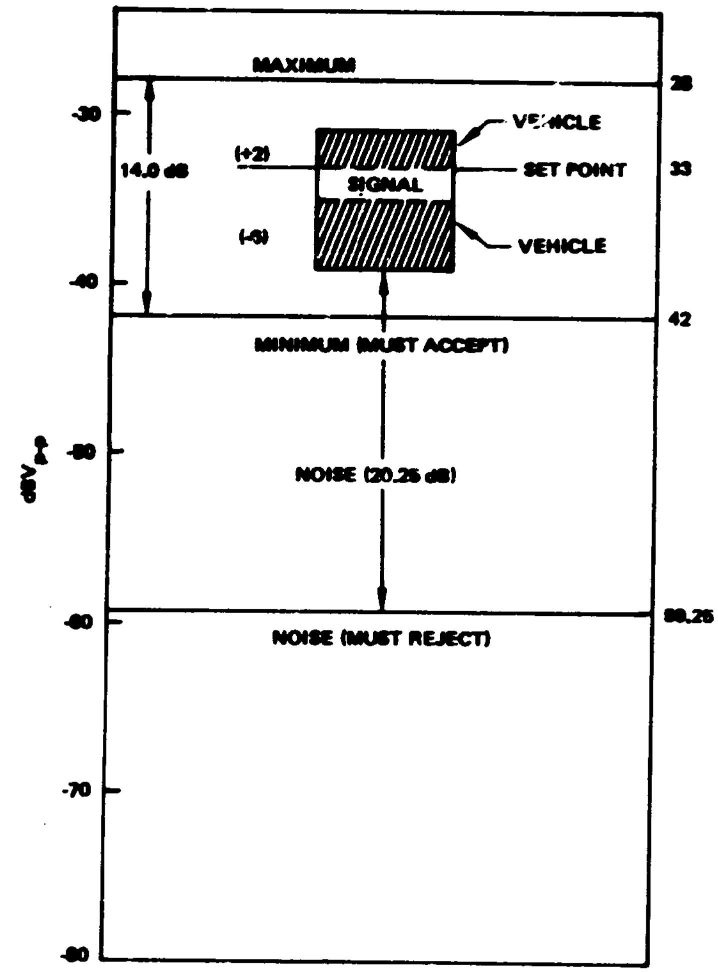


Figure 4-24. 13.3-kHz Signal Margin—Speed Tone B

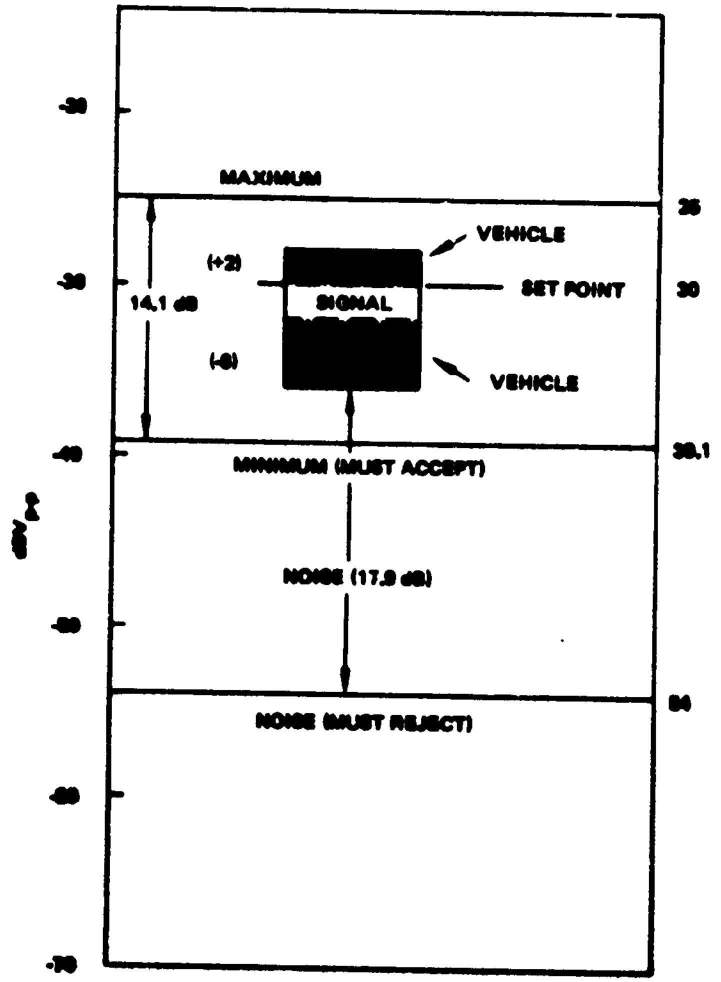


Figure 4-26. 17.2-kHz Signal Margin—Speed Tone C

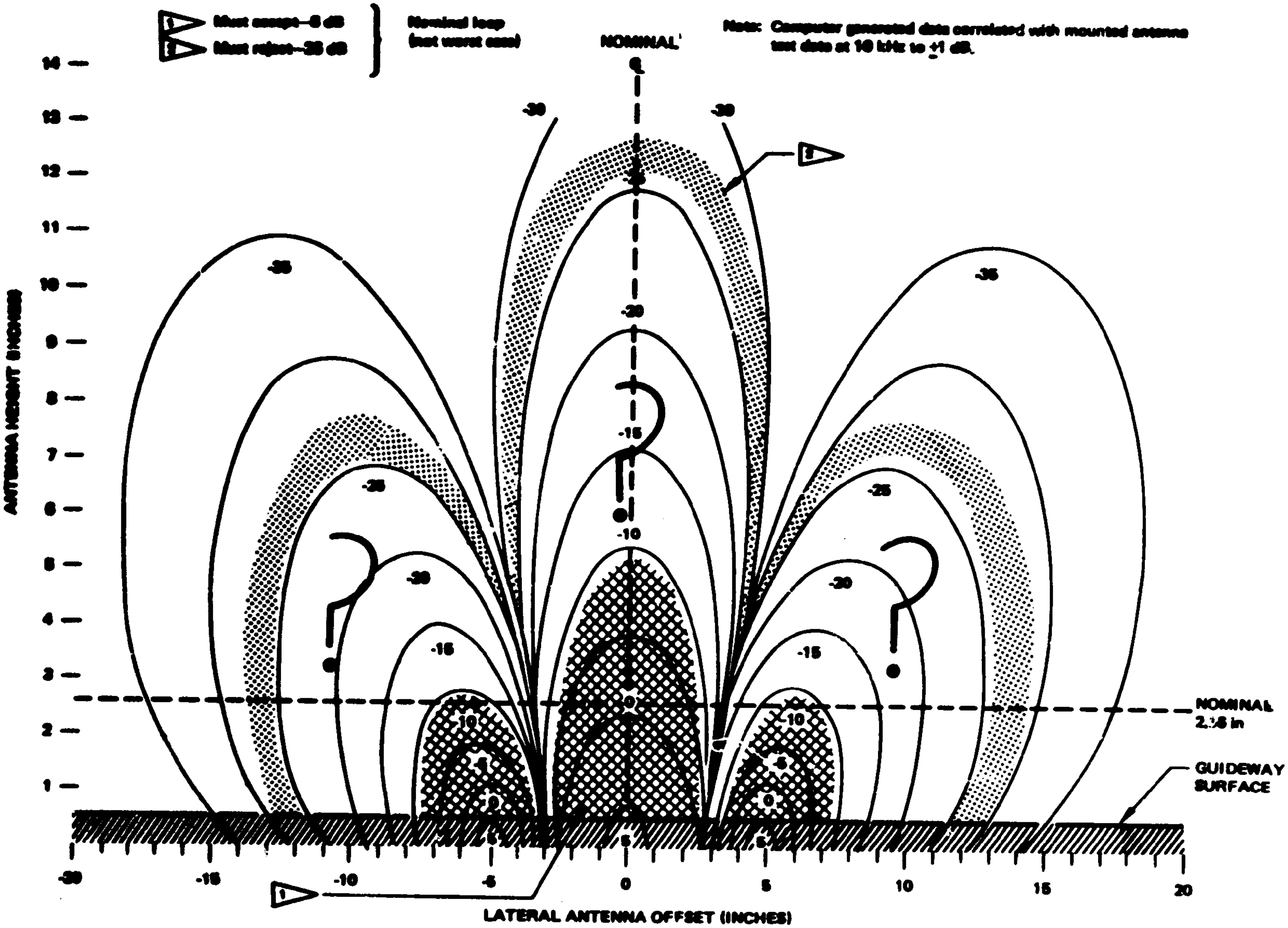


Figure 4-26. Signal Strength Pattern—6-in Loop and Bifilar Antenna

Section 4.3 develops the phase II signal operating points based on the desired signal margins and/or the predicted system performance based on the link model.

4.3 POWER BUDGET AND OPERATING POINTS (MPM-II)

Once an analytical model is developed to characterize portions of the communication system and the desired operating margins have been determined, it is necessary to apply this information to an operating point analysis to derive circuit design parameters. Figures 4-27 through 4-32 show the link analysis for each Morgantown uplink subsystem. The analyses represent design data for the phase II ICS system using the nominal VCCS input signal levels (set points) determined earlier. Each figure shows a sketch of the subsystem in block diagram format with the associated gains and losses representing the selected operating points underneath. The adjustment range or loss variation is also shown. All levels shown on the graph are in dBV rms and gains and losses are for voltage transfer, with interface impedances taken into account.

Analysis Methods and Data. Looking at figure 4-27 for the 6.1-kHz speed tone, note the VCCS signal thresholds shown on the right side of the chart. The levels are from the VCCS specification, where "max" represents the maximum signal input permitted for the VCCS to still meet specification on intermodulation, bit error rate, etc. The "must accept" level defines the point at which all VCCS's must detect the signal and the "must reject" defines the point below which all VCCS's must reject signals. In addition, we see the "nominal" signal level, which defines the guideway loop signal set point as determined by the signal margin analysis. The lowest level shown is the "max spurious," representing the level below which all communication system internally generated noise must lie. Examples of internally generated noise are intermodulation products, harmonics of lower frequency signals, and internal leakage or crosscoupling on circuit cards or within rack and drawer wiring. The voltage transfer ratio between the loop driver output and the VCCS input was derived from the loop transfer impedance previously mentioned, using approximate values for driving point impedance determined through analysis. Some uncertainty exists in the voltage transfer figure because of the variations in loop transfer impedance due to vehicle position, loop and feedline length, and antenna height, and because of variations in drive impedance due to loop length, geometry, and installation. Loop driver and FSK transmitter

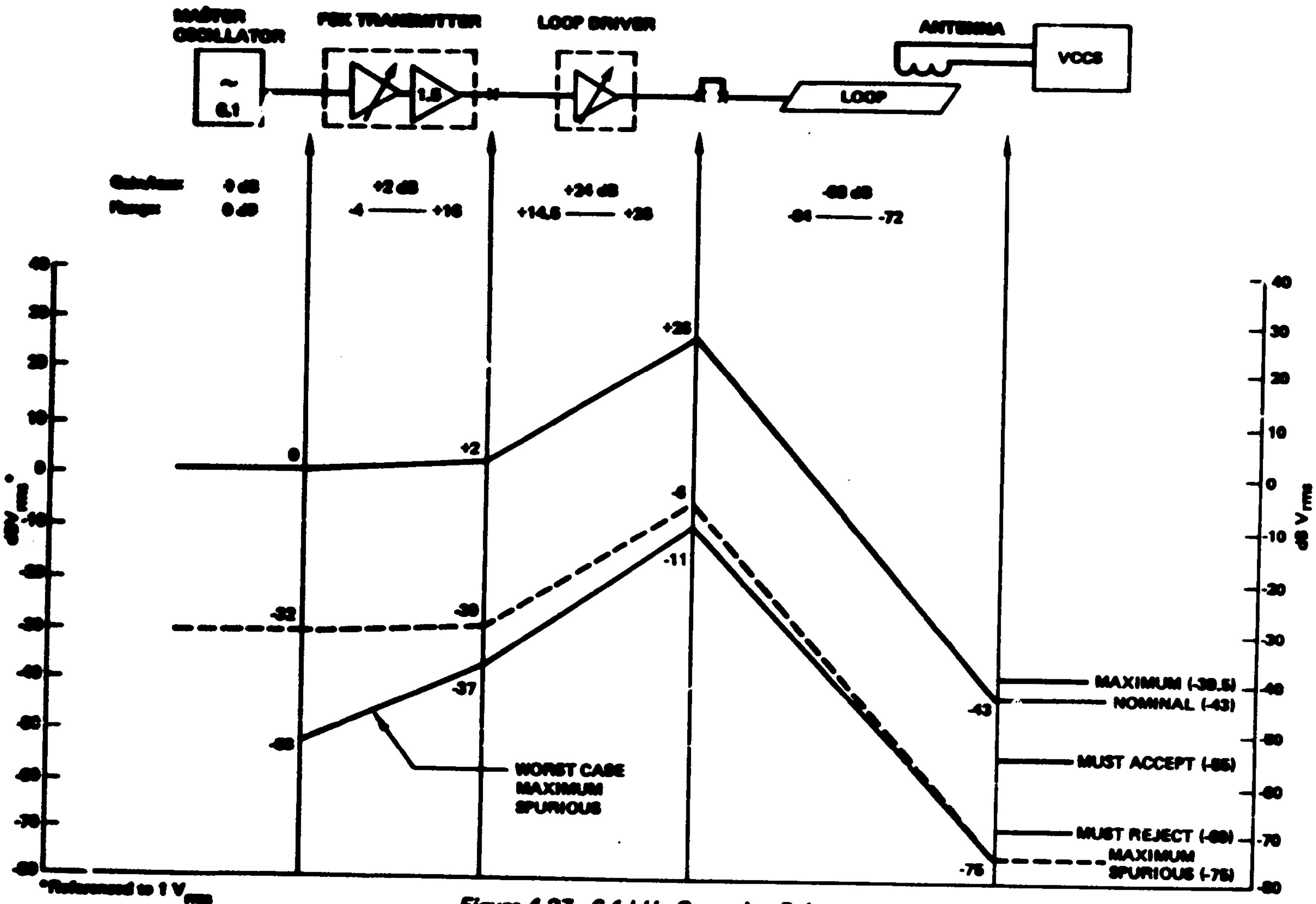


Figure 4-27. 6.1-kHz Operating Points

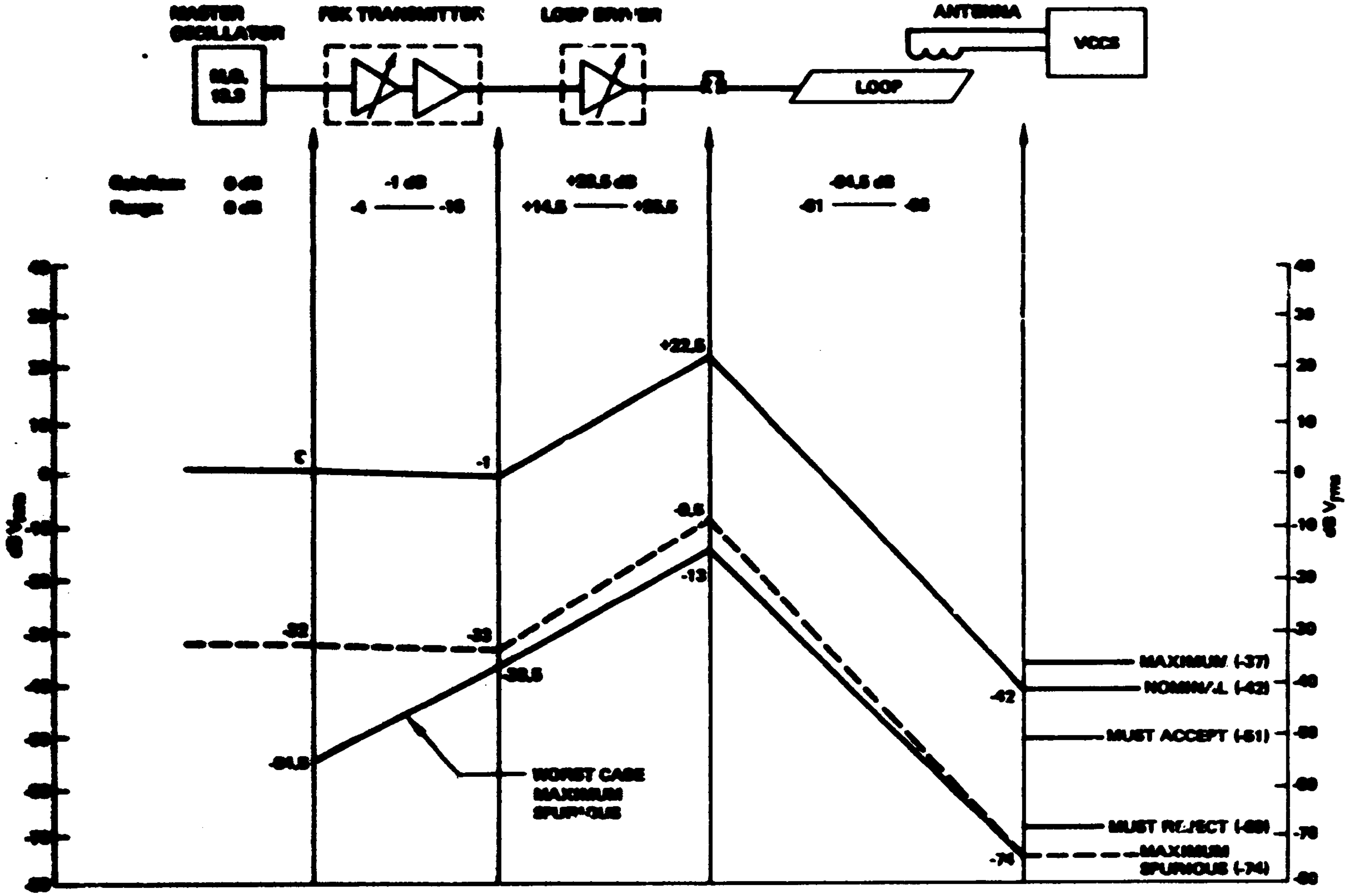


Figure 4-28. 13.3-kHz Operating Points

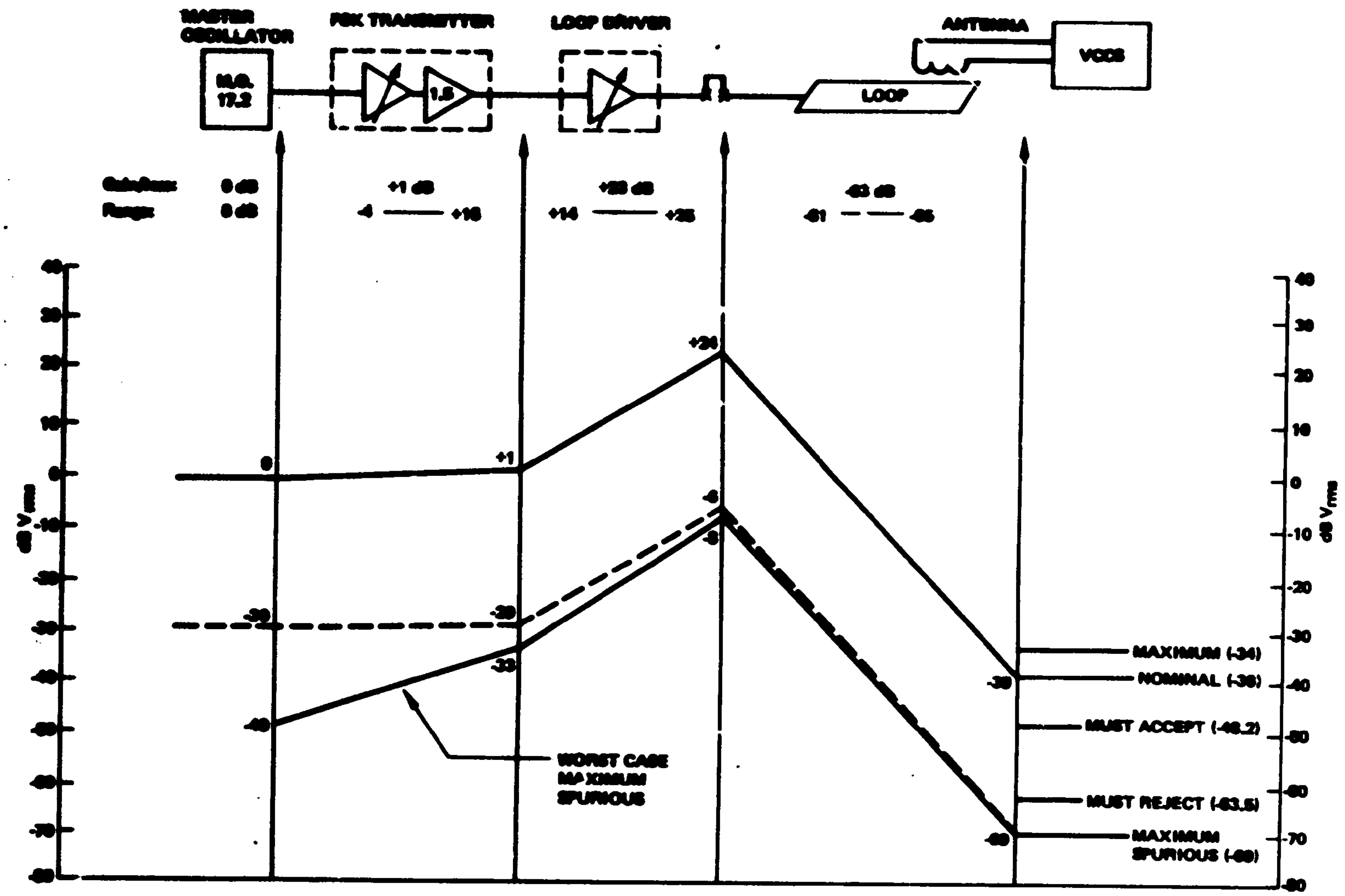


Figure 4-29. 17.2-kHz Operating Points

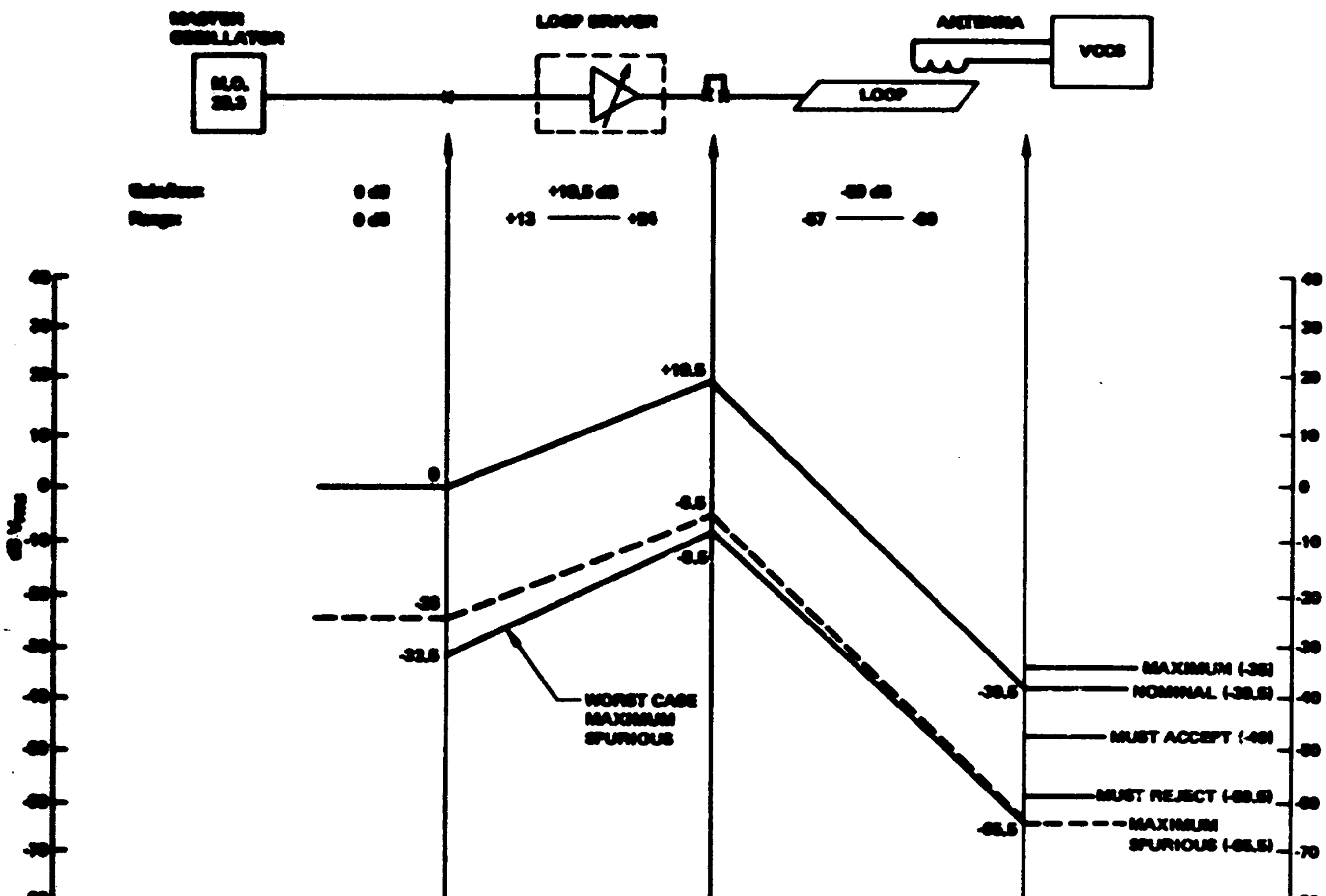


Figure 4-30. 28.3-kHz Operating Points

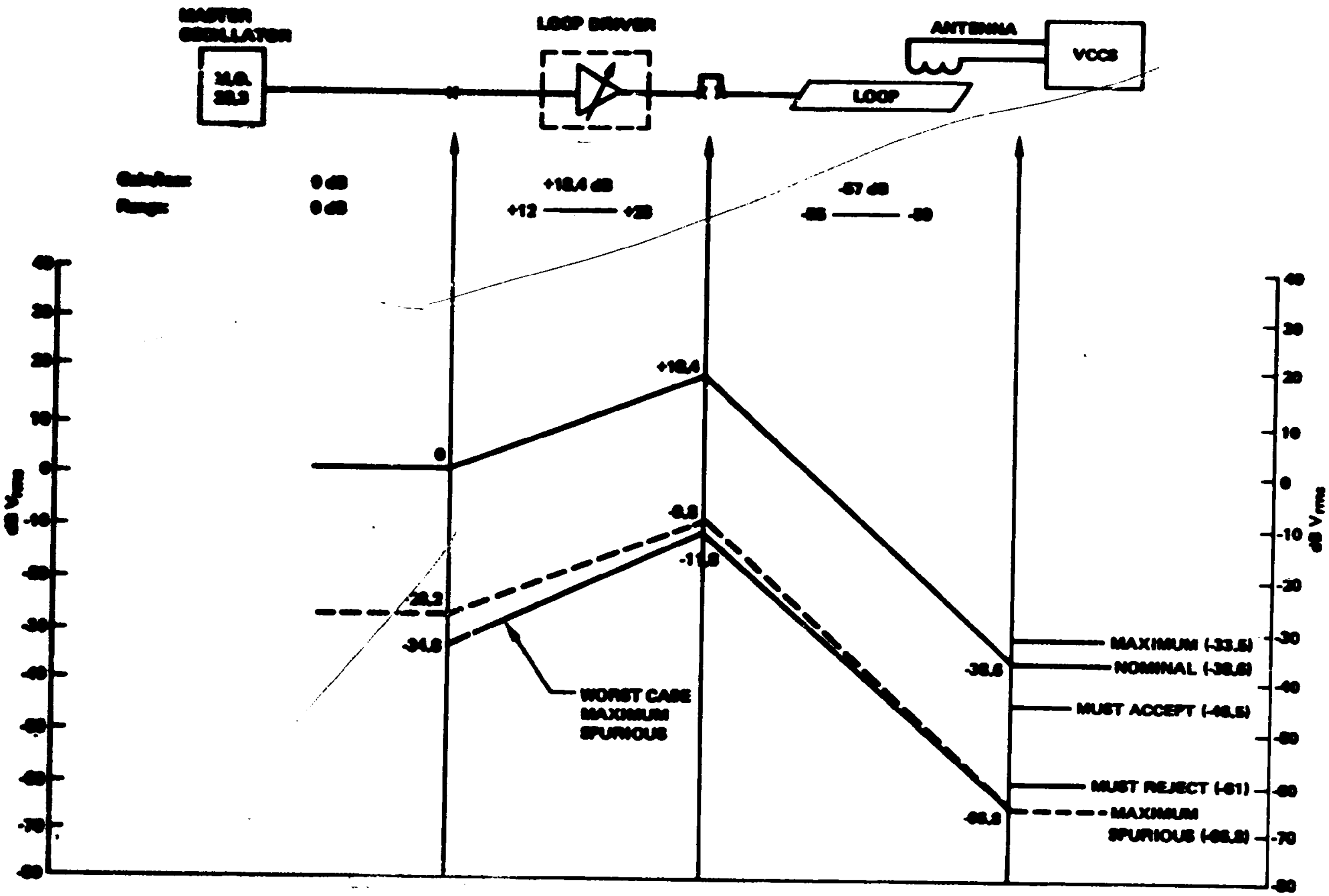


Figure 4-31. 36.3-kHz Operating Points

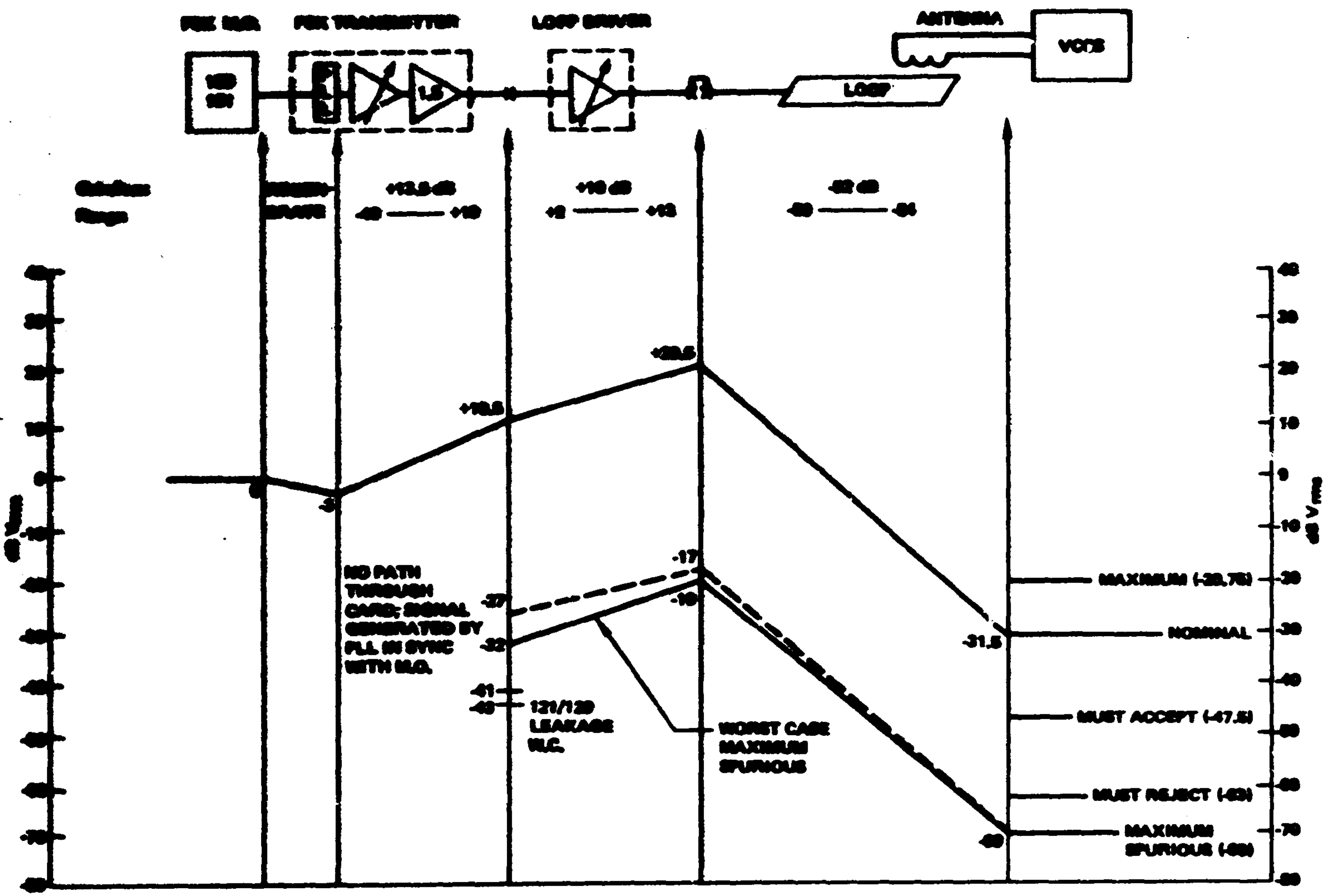


Figure 4-32. FSK Operating Points

voltage gains are self-explanatory with the ranges being the limits of the adjustment capabilities on the cards and all interface impedances taken into account. The master oscillators, with the exception of the FSK master oscillator, have a fixed output of Ø dBV rms.

Operating Points: Switch, CAL, and Stop. The operating points simplest to determine are for the 28.3-kHz switch tone and the 36.3-kHz CAL and stop tones (figs. 4-30 and 4-31). Using the switch tone (fig. 4-30) as an example, we note that the subsystem consists of a master oscillator feeding a loop driver that drives inductive communications switch loops coupled to a vehicle antenna supplying the signal to the VCCS. From the receiver requirements, we find that a nominal input signal (set point) of -39.5 dBV is required. Taking into consideration the guideway voltage transfer, we find that a loop driver output of +19.5 dBV is needed. Since the source is at Ø dBV, we set the loop driver gain to +19.5 dB, well within the capability of +13 to +24 dB adjustment range. It should be noted that the loop driver gains and adjustment ranges shown take into account the high-frequency rolloff designed into the loop driver amplifier. The rolloff is used to reduce amplification of harmonics and stray high-frequency signals.

Operating Points: FSK and Speed Tones. The FSK/speed tone subsystem represents the most complex subsystem because of the three to four tones requiring adjustment. The first adjustment is the FSK portion of the FSK transmitter. Here 121- and 129-kHz tones are modulated by a serial digital data word to form an FSK signal transmitted at a 1-kHz bit rate. As seen in figure 4-32, the subsystem consists of an FSK master oscillator, an FSK transmitter where modulation is applied, and an ICS loop driver. Similar to other subsystems, the loop driver feeds a guideway loop, which couples signals into the vehicle-mounted antenna connected to the VCCS. The FSK master oscillator signal is fed to all FSK transmitters in the station at a Ø dBV level. Because of the large potential for crosscoupling on the master oscillator card and within drawer wiring, the signal is isolated from amplification stages by using it only to synchronize phase lock loops on the FSK transmitter, which regenerate the pure FSK frequencies in sync with the master oscillator, without crosstalk. The FSK transmitter has a feature to allow transmission of continuous 121- or 129-kHz tones to facilitate adjustment. From figure 4-32 we find the nominal input signal to the VCCS is -31.5 dBV. Applying the guideway voltage transfer to -52 dB, we find that the loop driver output must be at +20.5 dBV (+10-dB gain) and the FSK transmitter must be set to +10.5 dBV (+13.5-dB gain). The reason for the large amount of amplification, as compared to some of the lower frequencies, is the nearly 13 dB of high-frequency rolloff in the loop driver used to ensure that any crosscoupled signals remain substantially below the transmitted signal level. Using good design practices, shielded cable, and single-point grounding within drawers and racks, at least 60 dB isolation is expected within the internal wiring. As can be seen from figure 4-32 the highest level signal is the master oscillator output at 0 dBV. With 60 dB isolation, this puts crosscoupled signals in the -49-dBV range—well below the maximum spurious signal line, which will be discussed later. Our only other concern is leakage within the FSK transmitter card, which also must be kept below the maximum spurious line at the card output.

Once the FSK signals are adjusted, the loop driver and FSK transmitter output stage gains for that loop are essentially fixed. Figures 4-27 through 4-29 show the link analyses for the three speed tone frequencies. By setting the loop driver gain to approximately 80 percent at the FSK frequencies, we obtain gains of +24, +23.5, and +23 dB at the speed tone frequencies, as shown in figure 4-33, a plot of loop driver gain and adjustment range versus frequency. The speed tones are supplied by the speed tone master oscillator and enter the FSK transmitter card at approximately 0 dBV. Each of two-speed tone inputs to the FSK transmitter card has an individual adjustment range of -4 to +16 dBV at the card input.

<u>Leakage, Harmonics, Crosscoupling, and Other Spurious Signals</u>. The two biggest problems associated with the earlier Morgantown ICS designs were harmonics of lower frequency signals appearing in passbands associated with high frequency signals, and leakage of 121- or 129-kHz energy into the transmitted signal. Precautions have been taken in the phase II design to avoid a recurrence of these problems. To effectively deal with the spurious signal problem, it is necessary to understand a little of the operation of the VCCS receiver. The primary concern is with the receiver detection threshold. Figure 4-32 shows the VCCS performance specifications at the FSK frequencies. Because of the uncertainty created by parts tolerance and receiver-to-receiver variations, we have defined a "must accept" level above which all signals will be detected by the receiver and a "must reject" level below which all signals will be rejected. Since the interface is defined at the

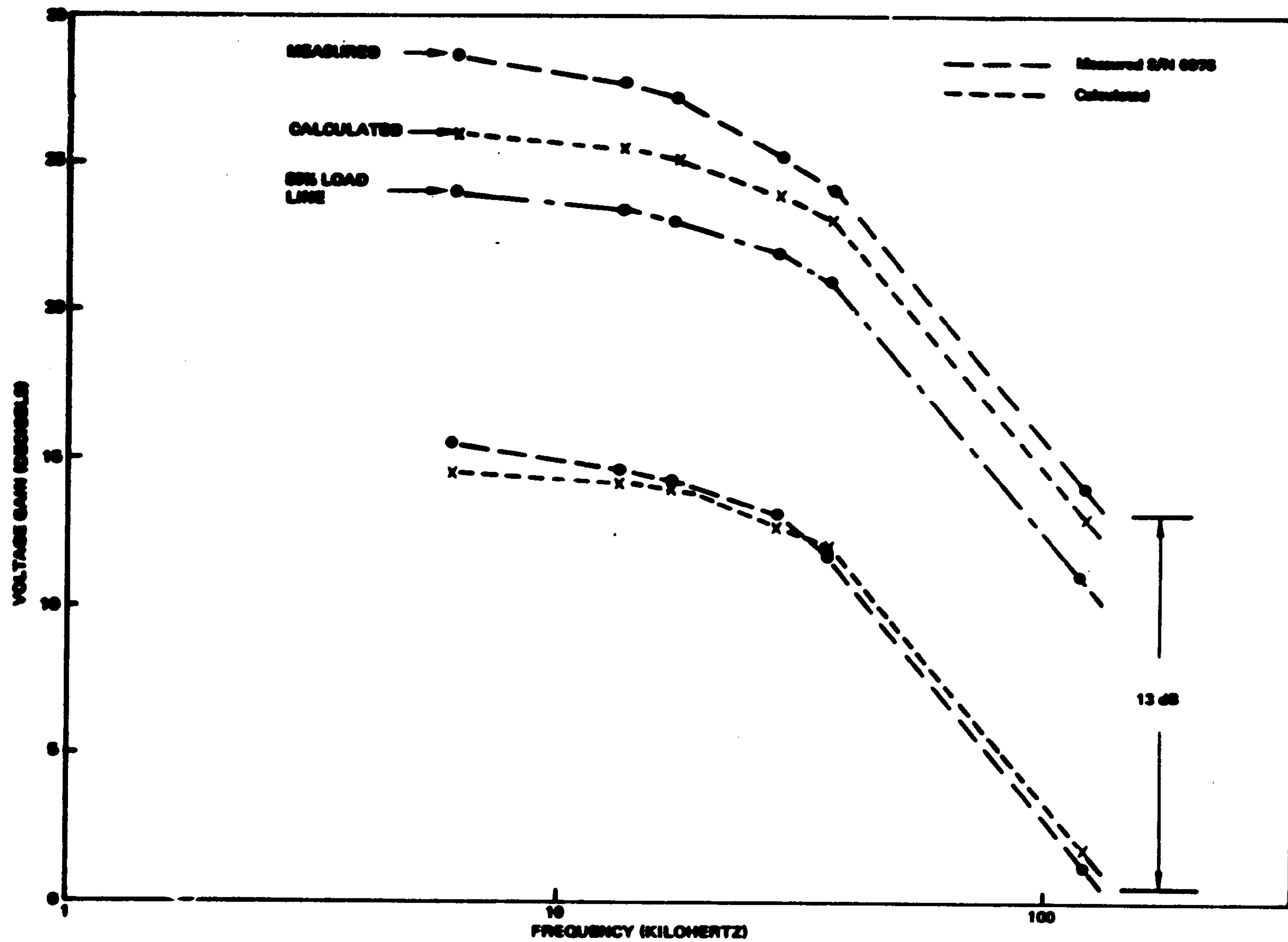


Figure 4-33. Loop Driver Typical Adjustment Range

VCCS input, we can then subtract 6 dB from the "must reject" level to account for guideway parameter variations and define a "maximum spurious" level below which all communication system generated noise must be kept. Our internal noise (spurious signals) is composed of harmonics, leakage or crosscoupling, and intermodulation products. The high-frequency rolloff in the loop driver coupled with low distortion (less than 2%) tends to reduce the magnitude of the harmonics in relation to the transmitted signal ahead of the guideway loop to vehicle antenna interface. This is essential since the inductive loop to vehicle coupling is better at the higher frequencies, as shown in figure 4-34, and were it not deemphasized prior to transmission, the signal-to-noise (spurious) ratio would decrease through the link. The FSK leakage is treated in a similar manner since FSK (121 and 129 kHz) leakage entering the FSK transmitter through one of the speed tone ports would be attenuated considerably as it is passed through the loop driver, as would leakage appearing at the loop driver input. Figures 4-27 through 4-32 show the maximum spurious level reflected back through the link for both nominal amplifier gains and loop transfer impedance and for an anticipated worst case, consisting of maximum gain in all stages and a minimum loop transfer impedance. An analysis of the signal source levels versus this extrapolated noise floor indicates that in all cases an isolation of greater than 50 dB in drawer and rack wiring will be sufficient to prevent any interference.

Performance of this type of link analysis not only provides essential design data but also outlines signal quality requirements at each interface to aid in card level and drawer level system testing. Analytical data such as the loop-to-vehicle voltage transfer should be verified and updated by field and test data as soon as practical.

4.4 EMC AND NOISE ENVIRONMENT

The development of a link model and its use in arriving at design constraints, signal margin predictions, and system operating points yield a system whose performance has been optimized in a benign environment. Experience in the phases IA and IB systems and analysis of system operation have provided information on the noise environment in which the MPRT system is expected to operate.

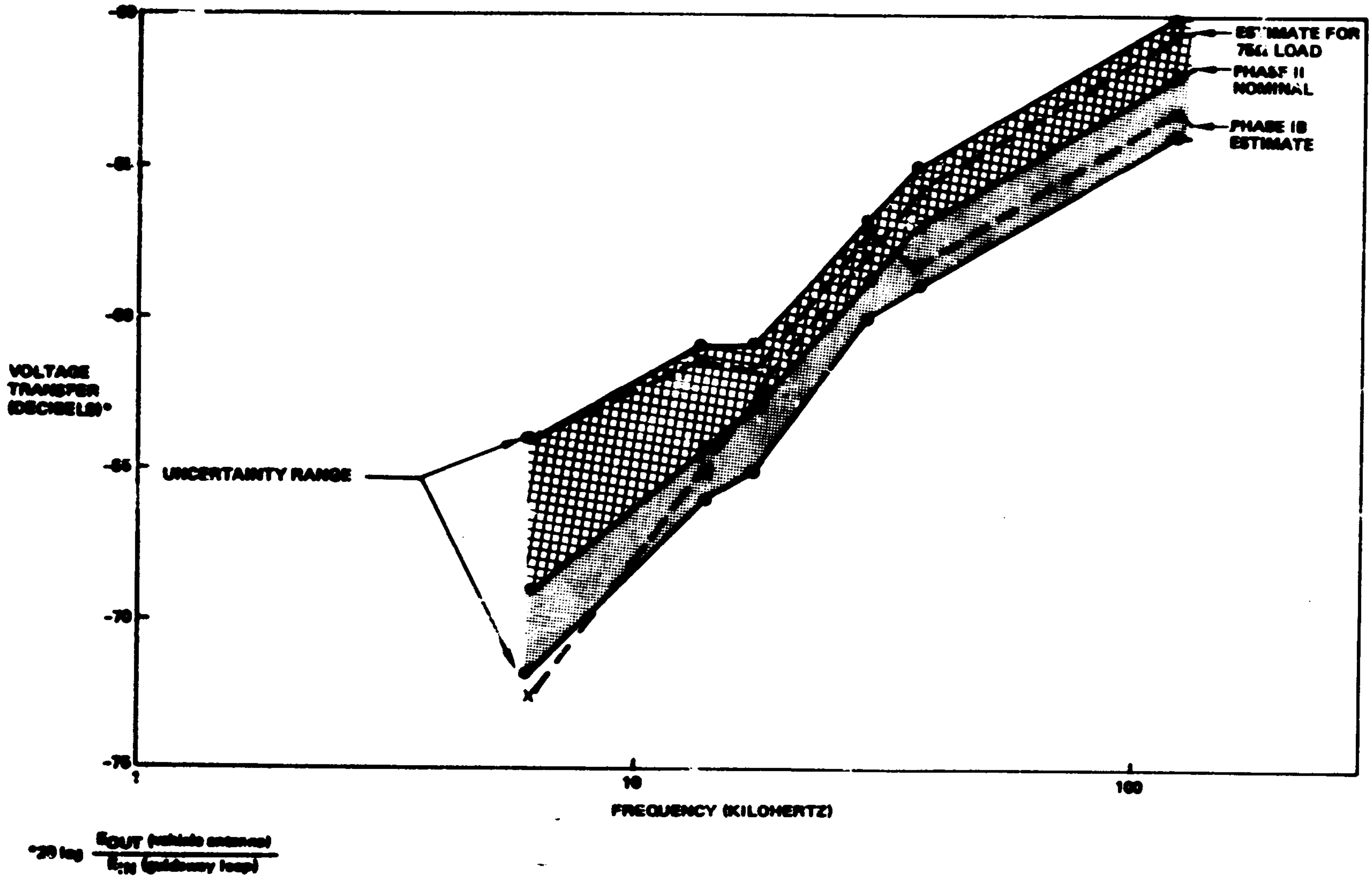


Figure 4-34. Voltage Transfer (G/W to VCCS)

The nature of the ICS uplink predisposes it to be vulnerable to Continuous Wave (CW) spurious signals in that the real signals are not greatly differentiated from simple tones; much of the foregoing report has dealt with CW spurious levels. Other kinds of interference are not so readily mistaken for signals, but, if sufficiently intense, can nevertheless prevent communication. The simplest categorization of other kinds is twofold: random and impulse. Random interference produces a phase-lock loop input voltage proportional to the square root of VCCS prefilter bandwidth; impulse interference produces a voltage directly proportional to bandwidth. Thermal noise is random, whereas pulses occurring at a rate numerically small compared to the bandwidth produce an impulse effect. MPM propulsion noise is of impulse type, but barely so; the repetition rate is sometimes 360 per second versus prefilter bandwidths of around 1000 Hz.

Table 4-4 summarizes nominal values of MPM interference ratios. Signal-to-noise density numbers describe the complex spectrums entering the VCCS receiver; to find the signal-to-noise voltage ratio at phase-lock loop input, one divides by the effective bandwidth of the (particular) prefilter.

TABLE 4-4 UPLINK TONE INTERFERENCE MEASUREMENTS

S/N RATIOS:	SPEED TONE A	SAFE TONE	STOP TONE	SWITCH TONE
Least Signal / Thermal Noise Density	Greater than 110 dB - Hz (40 dB-Hz is adequate.)			
Least Signal / Impulse Noise Density	61dB-Hz	66dB-Hz	75dB-Hz	77dB-Hz
FALSE LOCK MARGINS				
VCCS CW Threshold / Spurious Tone	16 dB	12 dB	17 dB	14 dB
VCCS Threshold Impulse Density / Impulse Density	NO DATA	16 dB (Must have at least 6 dB)	NO DATA	NO DATA

Note: These data are nominal for Phase II.

As an example of signal-to-noise ratio, the specified minimum phase II safe tone signal is 6 mV p-p, 2.1mV rms, and this is immersed in a propulsion controller impulse spectrum of about 1 μV rms per hertz. The ratio of signal-to-noise density is thus about 2100 (volts/volt) Hz or 66.4 dB-Hz. After band limiting by the input filter, whose 3-dB bandwidth is 770 Hz and impulse bandwidth about 1000 Hz, the worst predicted signal-to-impulse-noise voltage ratio becomes 2100 Hz ÷ 1000 Hz or 2.1 (or, 66.4 - 20 log 1000 = 6.4 dB). This ratio can degrade well below unity without consequent loss of lock. Therefore, at most, 60 dB-Hz of signal-to-impulse density ratio is necessary for the signal to compete with the noise.

The above signal-to-noise ratio is not the most important ratio for the safe tone channel. The lowest trouble threshold for this (and the stop tone) receiver is not lost lock but false lock. Pulses occurring during each 10-ms safe tone carrier-off period can cause momentary closure of the phase lock loop output switch (fig. 4-35), and this constitutes apparent lock. The criterion input ratio is the threshold impulse density divided by actual impulse density. This threshold is difficult to find because it depends on pulse reoccurrance rate. For the most common MPM pulse-to-pulse amplitude distribution, the threshold for channel failure (50-Hz filter ringdown) is about 9 mV p-p or 6.4 mV rms equivalent in a bandwidth of 1,000 Hz, corresponding to a density of 6.4 μV rms per hertz. The noise density at the test track, as noted, is about 1 μV rms per hertz, which is about 1 mV in the above bandwidth. So the margin against channel failure due to phase lock on pulse noise is about 6, or 16 dB. This assumes a most-sensitive receiver operating at the noisiest part of the test track.

The above discussion of the safe tone pulse interference applies to all uplink tone channels: The significant ratio in all cases is apparently threshold to noise, not signal to noise.

Short-duration false lock does not affect speed commands, but is a serious threat to the high information rate channels; i.e., safe tone, stop tone, and switch tone.

The most important noise source is the motor controller. Although this design is essentially unchanged in phase II, the guideway and power collector have changed in ways that may affect the VCCS input level significantly. This possibility is being investigated.

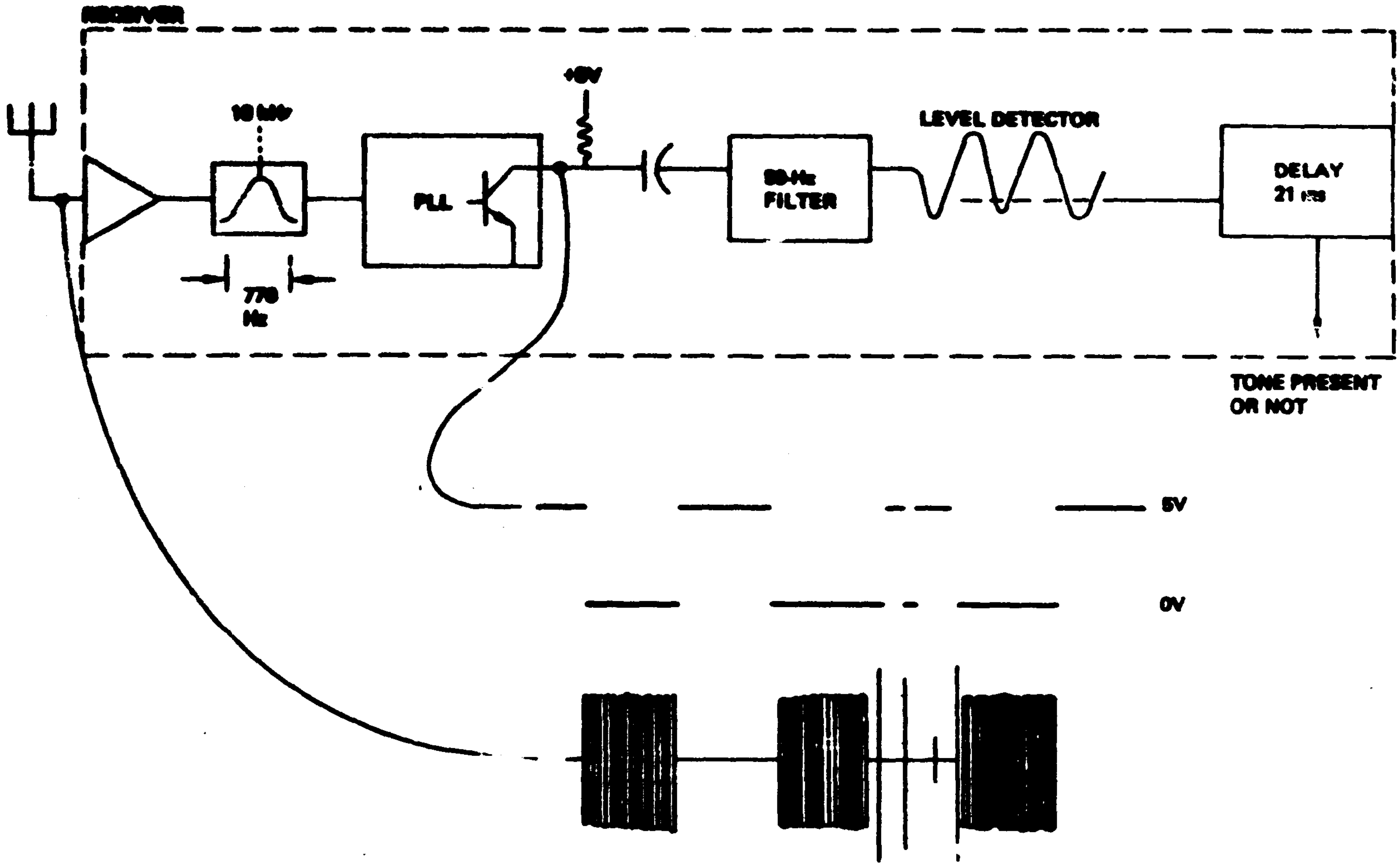


Figure 4-36. Phase Lock Loop Tone Receiver

4.5 FREQUENCY SELECTION

Analysis of communication frequencies selected for use on the link warrants discussion, even though it is unrelated to the link model.

An analysis of the frequency selections made for the MPM system reveals an interference potential from harmonics of lower order frequencies. During the frequency selection process in the Johns Hopkins report (sec. 3.1.3.6) some assumptions were made that did not prove to be valid for the system as designed. First, it was assumed that the second and third harmonics would be the only ones of significance. As shown in table 3-14, this was not the case. Due to the inherent high-frequency emphasis of the inductive link, up to the ninth harmonic has been found to be significant from an interference standpoint. Second, the bandwidths used in the frequency selection analysis were narrower than some used in the final VCCS design, thus allowing harmonics to fall within the active portion of other receiving channels. When problems were first encountered it was too far downstream to change frequencies; so the problems were addressed by changing sensitivities and receiver thresholds and by reducing distortion in the station electronics. It should be noted that the beneficial effects of vital tone encoding (sec. 3.1.2.3), using modulation on the low-frequency carriers, were to some extent offset by using the same modulation frequency for nearly all vital tones. This created the situation where harmonics falling within higher frequency passbands had the same modulation as the desired tone and were therefore detectable. Lastly, the Johns Hopkins/APL report assumed no frequencies over 30 kHz would be used, while the final system used the 96- to 129-kHz region for FSK communications and 36.3 kHz for the calibration/stop tone. These later additions were affected by harmonics from the frequencies under 30 kHz, and interference problems did occur.

5. RECOMMENDATIONS

The preceding sections extensively discussed the design evolution of the MPM Inductive Communication System (ICS). In retrospect, it is clear that certain elements of the ICS design are more critical than others to the successful implementation of an inductive communications concept. Recommended considerations for these critical areas are summarized below.

<u>Frequency and Modulation Selection</u>. Careful consideration should be given in future designs to the selection of signaling frequencies and modulation. In the MPM system frequencies were originally selected in the 6- to 36-kHz region, an area where the tones and their transmission behave much like audio. To satisfy the need for digital communication, additional frequencies were selected in the 96- to 129-kHz region. This is an area where the signals and their transmission begin to behave like RF; i.e., with standing waves and all associated problems. It has been found that optimum design methods for the two types of signals are sometimes mutually exclusive, thus requiring compromise early in the system development.

It is recommended that future systems use frequencies in the 70- to 135-kHz region. If frequencies in this range are used, and design considerations for RF are incorporated, it is felt that a much more reliable system will result. Using these frequencies, no harmonics or intermodulation products would fall within the active portion of the spectrum. Also, this close grouping of frequencies is very advantageous for signal transfer and impedance matching.

The a.c. modulation technique used on vital signals was successful and is recommended for consideration in future systems; however, care should be taken to use a different modulation for each signal and ensure that the frequencies chosen are not harmonically related.

<u>Loop Impedance Matching</u>. In the MPM system proper impedance matching in the guideway loops, feedlines, and terminations was not emphasized and, as a result, significant standing waves and a lower than anticipated efficiency was observed. For the MPM system the optimum impedance is around 150 to

200 ohms. To this end, some investigation has gone into the selection of a different feedline, because the one used was less than 100 ohms at most frequencies. The Belden 9182, 150-ohm "Twinax" shows some promise as a replacement for the twisted, shielded pair presently used. In addition to impedance matching, some consideration should be given to the placement of merges and demerges that appear as stubs on the loop. The stub length and placement will have a large effect on loop performance.

We recommend that measures be adopted to further optimize loop performance in any future system. One must determine the characteristic impedance of the guideway loops and properly match all portions of the guideway subsystem to the loops. This includes terminating loops in their characteristic impedance, developing a feedline to match the loop impedance, and providing proper signal transfer from the driver to the loop (transformer coupling is recommended).

Eliminate Multiloop Concept. Future systems should consider reducing or eliminating the multiloop concept used in the MPM system. There were significant problems and costs encountered in installing, maintaining, and balancing multiple loops in the same guideway slots. A viable alternative, if the multitone concept is necessary, would be the use of single loops (with a single current driver) capable of handling the multiplexed combination of all discrete tones. Some form of time slot assignments or synchronization of the modulation could be devised to limit the number of tones present at any instant to one or two; thus reducing the dynamic range required from the loop driver.

One other alternative is the adoption of an all-FSK system. Problems encountered in the MPM FSK system were of a design nature and, once resolved, yielded a reliable link. By increasing the data or message repetition rate, much of the data now sent by discrete tones could be incorporated into FSK messages.

Analysis Accuracy. The accuracy of link analysis should be improved by measurements of the loop and guideway parameters under actual conditions.

Parameters such as guideway common mode propagation, differential mode propagation, and characteristic impedance are difficult to calculate accurately; therefore, calculations are best backed up by field measurements.

Signal Margins. A systemwide effort should be made to maintain a satisfactory communication margin (signal to noise and signal to receiver threshold) because it is closely related to overall availability. To this end, an improvement in the receiver dynamic range over that used in the MPM system is recommended to accommodate greater signal variations. Also, it is essential that work be done to ensure electromagnetic compatibility (EMC) with the noise environment throughout system design.

Vehicle Design. Close coordination between vehicle designers and ICS designers is essential to ensure that vehicle dynamics are compatible with ICS design. Since the key factor in the ICS design is inductive coupling between the antenna and loop it is essential that antenna vertical and lateral displacement be limited to minimize signal level variations. Vehicle design should also consider routing propulsion power lines to minimize mutual inductance between them and the vehicle antenna.

Maintenance. To ensure the highest possible transportation system availability, a preventative maintenance plan should be instituted that monitors guideway signal levels and loop degradation (primarily isolation). The more frequent the inspection, the less the risk of downtime. In our experience many of the ICS failures are of a slowly developing nature and cause the system to become marginal before a hard failure is evident. Therefore, a guideway signal level monitoring vehicle is recommended. This vehicle could be dispatched into the normal traffic flow and would annunciate marginal areas to allow off-hours repair.

Fault Annunciation. In the Phase II system fault lights (LED's) were incorporated into many of the circuit designs. Circuit card faults, in some cases, are "or-ed" to illuminate a fault light on the equipment drawer. This signifies the general location of the fault, while also displaying an indication on the card itself. This type of fault annunciation allows rapid isolation of the defective circuit card, thus reducing system downtime when a failure occurs.

It is hoped that the above recommendations will prove to be of some assistance to those contemplating an inductive type of communication system. Our overall experience has been favorable and it is felt that this mode of communication has satisfactorily met the Morgantown system requirements.

APPENDIX A

REPORT OF NEW TECHNOLOGY APPENDIX

A review of work performed under this contract has revealed no innovation, discovery, or invention. However, this report, for the first time pulls together all available information which will aid future designers of Inductive Communications Systems. For example, section 3. details the MPM design evaluation with emphasis placed on the problems encountered and the rationale for the final design solution, and the system design guideline. Section 4. details the analytical approach and design analysis used to develop design requirements and operating parameters with examples given to show the MPM system performance. Section 5. contains recommendations for the best approach to the design of future Inductive Communications Systems.