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MORGANTOWN PEOPLE MOVER
ELECTROMAGNETIC COMPATIBILITY PROGRAM

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Automated Transportation Systems
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FINAL REPORT

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16. Abstract

Electromagnetic compatibility experienced in the Morgantown People Mover System is compiled and assessed. The evolving understanding and verification of this experience is compared with the ideal course of events as now perceived. In this way, the experience is made available to future transportation system developments.

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PREFACE

This report documents the Electromagnetic compatibility (EMC) experience obtained during the design and development of the Morgantown People Mover system. The EMC requirements, methodology, assessment, and recommendation for improvements 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 EMC control planning and design assessment were accomplished by the Boeing Aerospace Company, Seattle, Washington and applied to equipment provided by Boeing, Bendix Corporation, Ann Arbor, Michigan and other subcontractors to Boeing. Some of the early studies and design decisions were made by Jet Propulsion Laboratory, Pasadena, California. This report was contracted for by the Transportation Systems Center (TSC), Cambridge, Massachusetts.

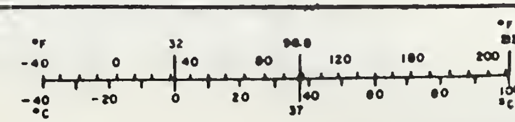
METRIC CONVERSION FACTORS

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

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



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1.0 INTRODUCTION

1.1 General

This report summarizes electromagnetic compatibility (EMC) experience with the Morgantown People Mover (MPM) system. The MPM was developed in three phases, and this report presents a collected analysis of design versus experience that occurred over a 10-year span. It concludes with some observations of possible importance for development of similar systems.

This section and the next provide background regarding the development of the MPM system and its current configuration. The remaining sections discuss EMC. Section 3 presents conceptual and practical EMC requirement considerations and describes the resulting requirements. Section 4 outlines analysis and testing performed to verify EMC. Section 5 details EMC problems unique to MPM. Section 6 suggests refinements and extensions which might be considered for application to future systems.

1.2 History

The Morgantown project began in 1969 as an Urban Mass Transportation Administration (UMTA) demonstration program providing personal rapid transit 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 system that consists of a fleet of electrically-powered, rubber-tired, passenger-carrying vehicles operating on a dedicated guideway network under computer control. The driverless vehicles automatically follow guiderail along the guideway. The on-board switchable steering concept was originated by the Alden Company of Natick, Massachusetts. The MPM project began with a research grant given to WVU in 1969. Initially, it was to be an expanded version of the Alden system. 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) of Pasadena, California was selected as system manager and designer in 1970. In May 1971 contracts were let to The Boeing Company, Seattle, Washington for vehicle design and fabrication and to Bendix Company, Ann Arbor, Michigan for communications and control of a six station system.

During the first half of 1971, JPL conducted a series of design trade studies resulting in the selection of a control and communications system (C&CS) incorporating the major design features of the current C&CS. The system selected included a collision avoidance system in addition to, and independent of, the normal operational control of vehicles. The operation control system incorporates synchronous operation of vehicles which are controlled by "point follower" as opposed to "vehicle follower" control laws. The point follower control scheme assigns vehicles to virtual time slots which conceptually move along the guideway with fixed headway according to a predetermined speed profile. The collision avoidance system independently enforces vehicle separation requirements to avoid possibility of collision should normal control malfunction.

In September 1971 with much of the system design completed, UMTA transferred system management responsibility from JPL to Boeing. Also at this time the program was phased first to build a three-station system (Phase I) and later to expand to a six-station system in Phase II. The development phase of the three-station system (Phase IA) began in 1971 and ended in 1973 (Figure 1-1).

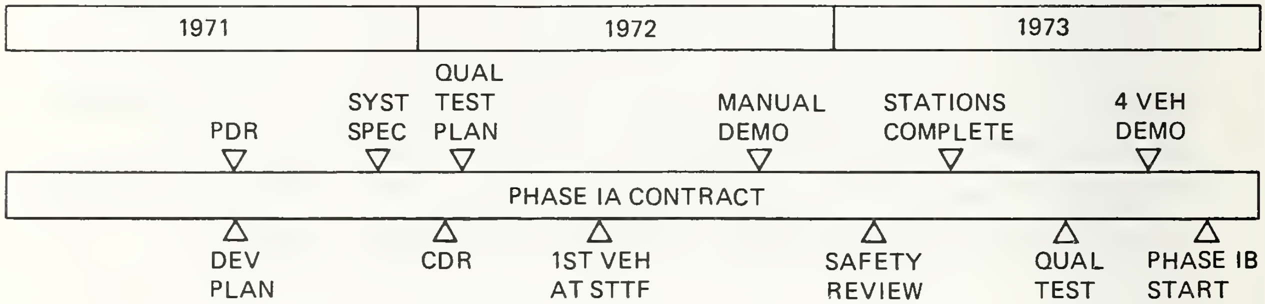

FIGURE 1-1. PHASE IA CALENDAR

This phase 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 which began in 1973 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 was completed and passenger service was intitiated in September 1975 (Figure 1-2).

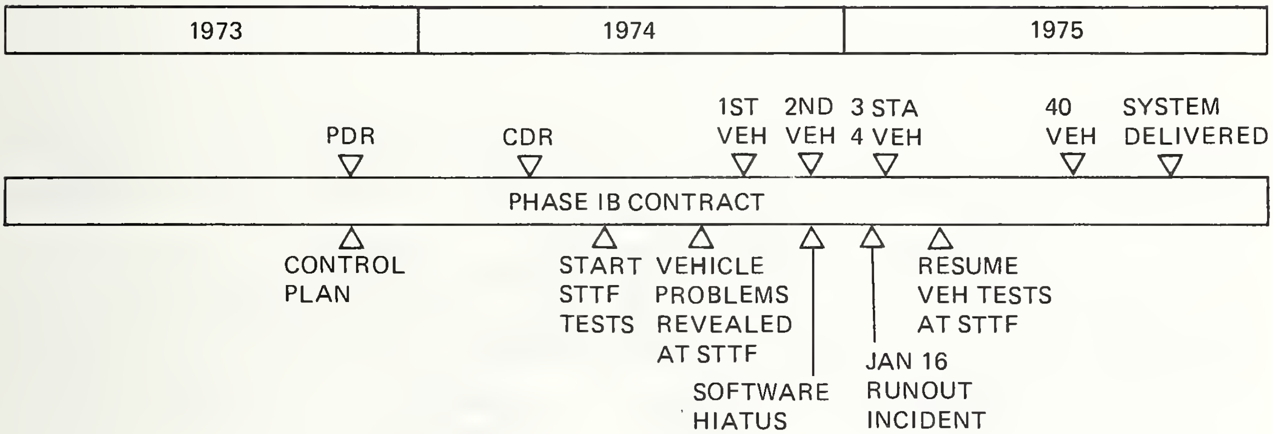

FIGURE 1-2. PHASE IB CALENDAR

Boeing was then awarded an operation and maintenance contract covering the first year of operation. During this time period many operational difficulties were resolved and desirable improvements were identified.

The MPM system performance was adequate to encourage WVU and UMTA to decide to proceed with Phase II expansion plans. These plans provided for two new stations and 3.4 miles of additional guideway to extend service to the Towers dormatories and the WVU Medical Center. Provision was included to expand the Engineering and Maintenance stations and to improve the system reliability. In November 1976 Boeing was awarded a Phase II contract for the above expansion and 28 new vehicles. For Phase II the CAS design was essentially unchanged except for the use of microprocessors to replace hardwired logic in the new and expanded stations. The Inductive Communications design also was basically unchanged. However, the refinements led to extensive re-packaging.

Phase IB passenger service was terminated in July of 1978 to allow guideway modification and installation of new equipment for Phase II. Installation was completed in June 1979, and passenger service was restored in July (Figure 1-3).

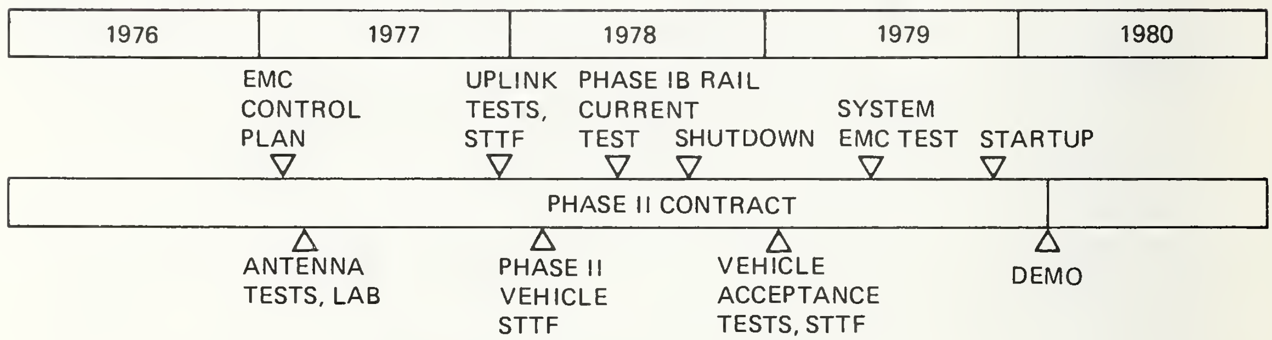

FIGURE 1-3. PHASE II CALENDAR

2.0 SYSTEM DESCRIPTION

The MPM system to be described is the Phase II system which entered passenger service in July 1979. MPM is an automated system which provides personal rapid transit between the three separated campuses of West Virginia University and the Morgantown central business district. A fleet of 73 electrically-powered, rubber-tired vehicles of 21-passenger capacity is operated at speeds up to 30 mph on a dedicated guideway at 15-second headways (vehicle separation). MPM transportation is safe, comfortable, low polluting, and reliable. The system features direct, nonstop, origin-to-destination service and operates the year around.

The MPM is operated in either schedule or demand mode. During those periods when passenger demand is highly predictable, vehicles are dispatched between origin/destination pairs on a preset schedule. When passenger demand is less predictable, vehicles are dispatched only in response to a passenger request.

Passenger actions upon entering the system are the same regardless of the mode in which the system is operating. The passenger arrives on concourse level at the origin station where static and dynamic displays provide direction to the platform servicing the desired destination and then proceeds to the platform level. There, the passenger inserts a coded card or exact change in a fare gate/destination selection unit and presses a button selecting destination. Gate and boarding displays then guide the passenger to the vehicle.

Assistance, if needed for any reason, is available through a dedicated telephone link to the central operator which is located near each entry gate area. The passenger boards a vehicle when it arrives at the loading gate and is conveyed non-stop to destination. At the destination station the vehicle stops at an unloading gate and then advances to a loading gate.

Vehicles are dispatched and monitored by 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.

The MPM system is comprised of three major elements: the vehicles, the guideway and electrification system, and the control and communications system (C&CS).

2.1 Vehicle

Lateral control is effected mechanically. Aside from a hydraulic pump the sole electrical element is a pair of solenoid valves that control rotation of a large "steering bias" spring into either the "guide right" or the "guide left" angular position. Control of the solenoid valves is one function of the VCCS which, in turn, receives a switch message from a wire loop in the guideway bed.

Longitudinal control is effected by two control loops. In the primary loop the Vehicle Control and Communication Systems (VCCS), a large box at the rear of the vehicle, receives a speed command and a safe-to-proceed tone from the guideway bed; it then issues either a speed command to the propulsion control unit, a larger box under the left side of the frame, or a brake command to the brake servo-amplifier located in the dc panel under a right-hand seat. This loop is closed back to the VCCS by actual speed information derived from a pulse-rate encoder on the driveshaft. This encoder also serves as an odometer in measuring the apparent length of calibration wire loops in the guideway bed, and in this way the speedometer circuit in the VCCS is calibrated for tire-rolling radius. In the secondary longitudinal control loop the propulsion control unit receives actual speed via the pulse-rate encoder, and this loop eliminates jerks.

The VCCS operates the vehicle doors in response to a digital data uplink message. Other such messages cause the VCCS to transmit (via a frequency-shift-keyed downlink to the nearby station) vehicle fault status, door status and vehicle identity. Certain faults (e.g., overspeed) cause the VCCS to stop the vehicle.

The VCCS contains six uplink tone receivers employing phase-lock loops to indicate the presence of the uplink tones. Three indicate civil speed; one is a stop message; one is a switch message; and one is a safe-to-proceed message. A seventh receiver decodes digital data from a frequency-shift-keyed (FSK) uplink. All seven uplinks are received on an uplink antenna mounted to the right front wheel axle-kingpin assembly. The antenna is a redundant pair, each consisting of two vertical loops connected in differential mode to the VCCS. The resulting pattern presents a null to the magnetic field of the power rail.

Downlink communication consists of the above noted FSK message channel and a facsimile of the switch message uplink tone called "Switch Verify". This facsimile is used by the collison avoidance system. The downlink antenna is located on the left front wheel axle-kingpin assembly and couples to FSK and Switch Verify loops laid in slots along the left side of the guideway.

Vehicle three-phase power is collected from power rails on either or both sides of the guideway and led to the wye primary of a transformer. One of the three leads (Phase B) is connected to vehicle frame. Propulsion motor armature power is derived from three autotransformer taps at 350 vac. Control and auxiliary power is derived from a wye secondary winding of which the neutral is connected to vehicle frame. The two dc supplies derive from this wye output. Both supplies are inside the propulsion control unit; one is for motor field excitation, and the other is for electronics(e.g., VCCS, battery charging, and relays). The battery's function is to maintain non-interrupted power to the VCCS and to a command radio receiver (remote control of VCCS power).

The vehicle noise environment is determined by the propulsion system together with door and steering control solenoids, namely:

- power collector brush arcing,
- armature phase-controlled rectifiers,
- auxiliary dc chopper regulated supplies (common oscillator),
- solenoids.

All DC motor commutation noise is filtered to levels below this environment. Air and hydraulic pumps are powered by induction motors. A 20-watt UHF transceiver antenna is mounted on the roof.

2.2 Guideway and Electrification System

The guideway map shows a two-way, continuous, trunk line (main guideway) augmented by a cluster of one-way ramps and channels at each station. The main EMC-related difference between the main guideway and the stations is the absence of electrification loops in the main guideway. The guideway provides a firm, straight curb for the Alden steering guidewheel; power rails; and a concrete running surface in which are embedded loops, magnets, and reed switches. Hot water pipes in the concrete and a resistance wire in each power rail enable winter operation.

A set of uplink communication single-turn loops 6 inches wide is laid in two slots along the right side just inboard of the wheels.

- Speed message is emitted by a two-tone loop extending the length of a speed zone. Frequencies are 6.1, 13.3, and 17.2 kHz. This loop also emits digital FSK messages on 121/129 kHz.
- Switch message is emitted by a loop about 60 feet long located at, and leading into, each merge and demerge. The 28.3-kHz carrier is modulated 70 Hz for left switch and 50 Hz for right switch.

- Stop message is emitted by a 12-foot loop at each berth. The 36.3 kHz carrier is unmodulated.

- Safe-to-proceed tone (safetone) is emitted by a continuum of loops laid end-to-end having lengths equal to the local safe headway distance (15 seconds of travel). The 10.2 kHz carrier is modulated 50 Hz.

- Calibration ranges 200 feet long beginning each 1000 feet are announced to the vehicle by a loop emitting 36.3 kHz, unmodulated.

At the forward end of each safetone loop are embedded presence detectors consisting of two sets of reed switches (each acting as a single switch) closed by a magnet on the vehicle. One of the sets informs the station computer of the "hit", and the other informs the station hardwired collision avoidance logic of the "hit". The computer prevents collisions by on/off control of the safetones based on the "software hit" data while the station electronics turn off relevant safetones in the event of disparity between the two "hit" messages from one reed switch set. A magnetic field of about 10 gauss will close an isolated reed, and some 20 gauss is needed to close an array of eight reeds. The loops carry currents of median value about ½ ampere, which corresponds to a field of 2 microtesla at a point 2 inches above the guideway at the bottom of the vehicle uplink antenna.

Magnets embedded in the guideway at switches and at station exits close reed switches in the vehicle which enable steering bias changes and high speed travel.

Electrification is by means of three stainless steel/aluminum power rails of which Phase B, the bottom one, is connected to structure at each station and to earth at each 22 kv/575v, 1000kva, power substation. In normal operation the rail is all interconnected, and all five substations are connected to the rail.

Electrification common mode loops are formed in the station areas by the ramp pattern, by vehicles bridging left and right side power rails, and by multiple connection to earth and structure. The vehicle power collectors are mounted on each front wheel spindle. Engagement is effected by arcing the rail ends away from the vehicle so that the collector shoes may slide in on a tangent. The Phase IB vehicle collectors were mounted at middle body, under each door, and were pneumatically articulated. Engagement was effected by extending the collectors into the power rail. One second later the opposite collector was retracted. The body mount concept allowed vehicle roll to force the collectors off the power rail at times.

2.3 Control and Communication System (C&CS)

The C&CS nominally includes the Vehicle Control & Communication System (VCCS), guideway loops, and the electronics in stations and central. As the VCCS and guideway have been described above, there remain to be described just the stations and central electronics.

Guideway loops and presence detectors are connected by cable to the nearest station. Control of a vehicle is "handed over" from one station to the next at the "handover" point located roughly midway between each pair of stations. With the exception of the safetone, which has a single-ended loop driver, the uplink shielded pair cables are met at the station with differential loop drivers. Downlink shielded pair cables are met with differential receivers. The two sets of presence detectors are met with two different types of discrete monitor, one a pull-up, the other a pull-down, so that a common mode transient will cause a disparity (safe) rather than a false "hit" (unsafe).

The station electronics consists of inductive communications drawers, collision avoidance drawers, and a dual computer. Inductive communications circuitry generates fixed uplink tones (e.g., for speed control) and provides carriers for messages being sent from the computer to the guideway (for door control, VCCS queries, switching, and stop/start). This circuitry also communicates downlink data (vehicle identity, fault status, and door status) to the computer and (switch verify) to the collision avoidance circuitry.

Collision avoidance circuitry accepts presence detector "hardware hit" data directly and "software hit" data from the computer; it also accepts switch verify data. The output is on/off control of individual safetone loops.

The computer on duty directs local traffic as requested by central control (switch and stop-start control) and hands messages along (door status and control; identity request and reply; fault status request and reply; destination selection and reply).

Central control consists of a dual computer, a "mimic" map of the guideway, a control console, and a communications console. Once the central operator has selected schedule or demand mode the computer software directs system traffic, operates the doors, and monitors the system for unsafe indications. Response to unsafe indications is automatic. The operator is a backup. The communication console enables communication between Central and passengers either on a platform or in a vehicle (by UHF radio). Also, the Central UHF transmitter is used to transmit tones which enable an addressed vehicle to become active or which disable an addressed vehicle. Also located at Central is a 50-Hz oscillator that provides synchronization to all safetone 50-Hz modulators; this enables smooth transit through station "handover" points.

3.0 EMC ASSURANCE

Electromagnetic compatibility of a transit system is the absence of interference between all parts of the system, and between the system and the community which it serves. The bulk of this section addresses system internal compatibility.

3.1 Community Compatibility

3.1.1 Introduction

Electrical interference between transit system and community is unlikely but also unpredictable; therefore, the transit system specification should require appropriate prevention. Criteria for interference (e.g., degree of annoyance to the community or disruption of transportation) are nowhere yet formalized, but criteria for both spurious and proper radiations have been issued by the FCC and the military. In addition to these limits there exists much scientific data on the noise made by cities and the noise inherent in the atmosphere. Criteria for susceptibility to emissions have been issued only by the military. Radio amateurs are seeking the imposition of radio wave susceptibility limits on home entertainment devices. About 10 years ago EMC and consumer electronics groups began building roughly quantitive models of utility ac power routes for electrical noise in passing from one consumer to another. This effort is still under way and is directed towards design guidelines for the susceptiblity and emission properties of consumer electrical equipment. Europe has already imposed conducted emission limits on consumer electrical equipment. Since 1970 The Bureau of Standards has become increasingly active in consumer electrical interference studies (e.g., CB transmitters versus electronic carburators). Although its role is non-regulatory the Bureau's work will probably form the basis of new design guidelines. Transit system EMC specifications (e.g. one by the SAE) are under development; whatever emerges will probably not exceed the scope of transit system internal compatibility. In summary, only the FCC regulations are mandatory at present (Table 3-1).

TABLE 3-1. TITLE 47 CODE OF FEDERAL REGULATIONS (47CFR)

PART 15 RADIO FREQUENCY DEVICES

- Devices transmitting at 10kHz and above to receivers more than $\lambda/2\pi$ meters away must be licensed whether open or guided waves are utilized.

- Needing no license are:

  1) Devices transmitting to receivers closer than $\lambda/2\pi$ meters away; these devices are called "restricted radiation" (RR) devices.

  2) Incidental emitters.

- The field strength limit for RR devices is 15 microvolts/meter at distance $\lambda/2\pi$ *

- RR devices emitting open radiation must put less than 1 (or 0.1) watt into the final stage.

- Incidental emitters are not limited.**

PART 93 MOBILE RADIO

Licensing and construction regulations are promulgated.

* e.g. inductive communications

** e.g. propulsion

3.1.2 Requirement

The system specification (Phase IB and Phase II also) requires that the system tolerate a stated environment and emit no signals above the FCC Part 15 limit. These requirements have been met, and no interference between city and transit system has occurred. However, the first requirement is not an adequate base from which to approach other situations. A more general approach will be suggested.

The MPM two-fold community EMC requirement is this:

"The system shall meet the performance requirements of the specification when subjected to environments caused by natural sources at levels described in ITT Reference Data for Radio Engineers (Fifth Edition), by industrial levels such as described in Overhead Power Line Tests in MIL-STD-461A, by c.w. levels due to broadcast and communication transmitters collocated with the system, and by interference sources within the system.

The system shall comply with the applicable sections of the Code of Federal Regulations, Title 47, Chapter I, Part 15 and Part 93 (Federal Communications Commission Regulations)."

The inadequacy in the first paragraph is that it arbitrarily defines the noise environment. Not only do the ITT and MIL-STD-461A references fix the noise field at a low level, but also there is no recognition of conducted noise from city to system. As an example of the low level, the stated noise environment is a factor 300 weaker than the power rail noise field measured at the vehicle uplink antenna.

This low environmental noise level was, and is, appropriate for Morgantown judging by extensive troubleshooting evidence; (oscilloscope and spectrum analyzer measurements in all parts of the system show only internally generated signal forms.) But at Morgantown there is neither heavy industry nor unusual electrical facility near the guideway. Also, the stations are well isolated from city power. This isolation might not be the case, for example, were a transit station to be located within a hospital, within a dormatory, or within an airport terminal. Then, the transit system could become a channel for conducted noise in the environment. The sounder approach to the specification is to require that the system perform properly in the presence of whatever electrical environment exists at the time of contract award. The procuring authority can arrange for a survey to define this environment.

The MPM requirement for tolerance of c.w. levels due to broadcast and communication transmitters collocated with the system could be worded better, but it exemplifies the approach just recommended. The c.w. environment is more likely to cause trouble than is the noise environment. (At the International Oceanographic Exposition at Okinawa, for instance, a nearby ELF navigation transmitter had almost enough power to pose a potential interference threat to the transit system inductive communication link.) Radar illumination can be a major threat. In summary, the c.w. environment of a transit system could be severe; consequently, the system specification should require success, not an arbitrary level of tolerance. The wording problem noted is two-part: navigational aids should be included; and the phrase "collocated with the system" is restrictive and should be omitted. MPM has not been affected by the waysidec.w.environment; however, the vehicle odometer has been inhibited by transmitters carried in the vehicle by maintenance personnel (at 450 MHz; the problem has since been corrrected).

Emissions from the MPM that might affect the city are only partly regulated by the FCC; therefore, the present compatibility is probably the result of a self imposed restriction. Setting aside the mobile radio there are two emissions of consequence from MPM:

- inductive communication uplink,
- propulsion controller noise.

The first is limited by Part 15 of 47CFR to 15 $\mu V/m$ at $\lambda/2\pi$ distance. The second is "incidental" and therefore is not limited.

Inductive communication emission met the limit and no interference has occurred. But Morgantown has no receivers at MPM uplink frequencies so that the appropriateness of the requirement is unknown. Nevertheless, the Part 15 limit is the best available. It is reasonable, and its wide promulgation creates authority. Expressed differently, if a transit system meets Part 15 and yet interferes with its community, then the transit system is not at fault.

Emissions from the vehicle radio are appropriately regulated by 47 CFR Part 93 insofar as community electronics is affected. However, Part 93 does not attempt to protect people from physiological harm due to radio. The possibility of such harm in MPM was investigated as a result of concern over the lack of shielding afforded by the fiberglass shell. However, the field immediately under the roof antenna is only 20 volts/m, well below the U.S. physiological limit of 194 volts/m. Artificial heart pacemakers have roughly the same sensitivity to rf radiation as the body (but react more swiftly). In summary, passenger exposure to ordinary radio communications fields is not a problem. Should an unusual transmitter be placed on a fiberglass vehicle, then physiological harm must be assessed. One source of data on heart pacemaker thresholds is the USAF School of Aerospace Medicine at Brooks AFB.

Propulsion controller noise is not limited by 47 CFR, and as a result might have been a problem in MF broadcast receivers. However, the EMC control plan limits this noise by imposing MIL-STD-461A RE-06 (overhead powerline broadband electric field). This control should have been in the higher level, system specification because community protection is not a transit system internal matter. Whether or not RE-06 is the best limit in a given situation will be found nearly impossible to determine. Nevertheless, the system planner must choose a standard of some kind (as distinct from a tailored limit) for the amount of broadband noise a transit system may emit.

A question on MPM emissions was posed by a University researcher who is installing an electron microscope quite near Beechurst station:

Will the guideway interfere with the microscope? Investigation showed that electron microscope susceptibility varies greatly with the quality of the instrument and that the real threat is noise on the ac powerline, not radiation. Beechurst draws its power from a dedicated MPM substation; hence, the researcher could be assured that noise conduction would not be a problem. This high degree of isolation will not necessarily be present in every case.

In summary, the recommended approach to community compatiblity is outlined in Table 3-2.

TABLE 3-2. PRESCRIPTION FOR COMMUNITY COMPATIBILITY

OUTLINE ITEM	APPROACH
1. Interference Criteria	No standards exist; innovate as needed.
2. Community Broadband Noise Emmission	Require transit system to tolerate whatever exists.
3. Community Radio Transmissions	Require transit system to tolerate whatever exists.
4. Transit System Broadband Noise Emission	Select a consensus radiation standard such as MIL-STD-461 RE06. Consider need for a conducted noise limit, or require no intererence.
5. Transit System Restricted Radiations (Inductive Communication)	Require 47CFR Part 15.
6. Transit System Radio Equipment and its operation	Require 47CFR Part 93.

3.2 System Internal Compatibility

3.2.1 Concept of Compatibility

The requirement that a transit system be self-compatible is largely implicit in its performance requirements. The system is supposed to do certain things with stated degrees of achievement. In order to do so the system must be "self-compatible;"(i.e., each function is achieved not only in solitary but in conjunction with the other functionings.) The explicit requirement of "compatibility" just assures the customer that what is expected actually gets delivered. This assurance is composed of two distinct elements: completeness and margin.

Completeness of a transit system's compatibility requires that the automatic functions work well in all reasonably probable cases and that the manual functions (e.g., schedule mode selection) can be done in any authorized combination in conjunction with the automatic cases. In other words, complete electromagnetic compatibility means that there is no interference between functions required to be electrically independent. But suppose that the air cooler shuts down just as the vehicle changes bias and that the resulting combined noise in the vehicle antenna threatens the uplink receiver. In this example, the idea of "completeness" requires that this combined noise be tolerable even though its occurance is rare. Clearly, there are practical limits on the completeness of any demonstration of compatibility. The usual approach is to test selected pairs of functions in an "all up" ambient and hope that multiple-function incompatibilities have been tested.

The element of "margin" in the compatibility of a system is a requirement that at every potential interference port the signal be less than threshold by a stated amount. (Either the signal or the port may be the spurious element in the interaction.) The first explicit requirement for margin of compatibility appeared in MIL-I-6051 about 1960. The earlier versions simply required completeness of compatibility. Recently, a more rigorous version of the margin concept has appeared in which the stated margin is entirely available for erosion by unknowns; the margin goal is demonstrated while all known variables are combining in the worst way.

The two elements, completeness and margin, supplement each other in that incompleteness of demonstration can be made up for by requiring a compensating margin increase.

3.2.2 Development of Margin Requirements

Risk criteria help identify circuits likely to malfunction due to interference. Criticality criteria help identify circuits whose malfunction could be so serious that such a likelihood is not a criterion. Combining vulnerability and criticality yields a complete criterion for selecting circuits required to have margin.

The amount of margin appropriate to a critical or vulnerable circuit depends on the range of variation of relevant parameters over the service life and with component variation. Variation with system mode (e.g., number of vehicles running) is included explicitly in the margin requirement. The choice of margin amount in decibels is, therefore, just based on

1. variation with time, and

2. variation from unit to unit.

For example, MPM uplink circuits were required to have 6dB of margin (threshold 6dB above noise).

3.2.3 Margin Demonstration Method

There are three approaches to demonstration of the margin of a circuit.

1. Increase the noise or interfering signal until malfunction results.

2. Lower the threshold of the receptor until malfunction results.

3. Measure noise, measure threshold, and compute the ratio.

These address margin in the MIL-E-6051 sense (i.e., threshold to noise). Sometimes the critical margin is not interference related (e.g. signal-to-threshold margin). Then, lowering the signal is an option. "Signal-to-noise" ratio is not generally a margin.

3.2.4 MPM Compatibility Requirements

Completeness and margin were introduced earlier as the criteria for system compatibility. For MPM the MIL-E-6051 margin approach was adopted; critical circuits were selected; then each was assigned a margin target based on a combination of criticality and estimated parameter variation with time.

The Phase IB critical circuit interface possibilities were identified in the control plan at the time of preliminary design review. These were:

1. Central computer - System support panel,
2. Central computer - Maintenance station computer,
3. Modem - Modem,
4. Station computer - DHU,
5. Station computer - CAS,
6. Station - Vehicle,
7. Station - Presence Detection,
8. VCCS - Vehicle.

Because of experience gained during development, the Phase IB test procedure reduced emphasis on station internal interfaces and increased emphasis on inductive communications; the objectives were:

1. 6dB margin on inductive communications:

on stoptone uplink,
on switchtone uplink,
on speedtone uplink,
on safetone uplink,
on safetone "off" level;

2. modem bit error rate to meet target during multi-vehicle operation;

3. 6dB margin on CAS master oscillator station interface lines;

4. 6dB margin on null modem lines;

5. Computer power input transients less than 140 volts.

At the start of Phase II, the control plan repeated these Phase IB objectives. Because experience indicated that the risk of interference was too slight to warrant test, the modem checks were dropped from test planning.

3.3 Risk Prediction

Most interference types are discovered the first time by accident because interference is by nature spurious, unforseen. About ten years after discovery of a type the interference specifications catch up, and prevention of that type of interference becomes routine. Consensus interference specifications (e.g., MIL-STD-461) are repositories of history and have use to the extent that a new system contains old combinations. For example, MIL-STD-461 is essentially a direct descendant of specifications created to prevent interference to communication receivers; thus, interference signal meters engendered by these specifications have narrow bandwidths. MIL-STD-461 is the correct requirement for hardware acquisition insofar as the MPM vehicle radio receiver is concerned. A different measuring bandwidth and limits would be appropriate for protecting an on-board microprocessor.

A new system, particularly one utilizing new technologies, may contain potential interference situations not preventable by procuring to meet MIL-STD-461 or other existing equipment interference specifications. Also, the expense of compliance with such a specification can be wasted if no radio equipments are employed. Automated transit systems increasingly employ new technology so that the correct way to develop acquisition requirements for electronic units is to perform a risk analysis.

It is now widely recognized that specific EMI risk should be the basis of requirement (i.e., should take priority over consensus standards). However, it is just as evident that the information and skill needed for a risk prediction that is superior to consensus may not be available to the contractor. Transit developments in particular cannot afford the intensive mathmatical modeling now becoming standard in military procurements. On the other hand, there are yet no concensus standards for transit EMI. In summary, the requirements have to be wrought by common sense from all sources:

1. specific risk,
2. similar transit experience,
3. consensus standards (e.g., MIL-STD-461).

A process by which a new system can be examined for risk of interference is described here. This process is analogous to present day computer schemes based on mathmetical models, but it includes only the electromagnetic concepts, not the mathmatics. The process unfolds in two parts: first, a matrix that orders the analysis, and second, the analysis. The matrix, in addition to ordering the analysis, also servces to cull from detailed consideration those situations known to be compatible.

3.3.1 Interference Matrix

The risk of interference between parts of a system can be evaluated in orderly manner by considering the elements of a square matrix of these parts.

Completeness is assured if the parts listed as rows and columns comprise the complete system of interest.

The matrix is constructed by partitioning the system in some way and then arranging these N parts both as row titles and column titles (Figure 3-1). In this way N^2 elements are generated:

N	diagonal elements representing part self-interferences,
1/2 N(N-1)	elements representing interferences from first-listed part to latter-listed part,
1/2 N(N-1)	elements representing interferences in the reverse directions.

INTERFERENCE RECEPTORS: →

INTERFERENCE SOURCES: ↓	VEHICLE		GUIDE-WAY	STATION	COM-MUNITY
	X	Y			
VEHICLE X	1	2			6
VEHICLE Y	2	1			6
GUIDEWAY			3		6
STATION	7	7		4	6
COMMUNITY	5	5	5	5	

Examples of potential interferences suggested by the matrix:

1. Vehicle self interference (e.g., uplink noise)
2. Vehicle interaction (e.g., uplink noise)
3. Loop crosstalk
4. Station self interference

5, 6. Community interaction

7. Station to vehicle interference (e.g., sidebands)

FIGURE 3-1. MPM TOP LEVEL INTERFERENCE MATRIX

In use, one asks for each element (i,j), in turn, whether part i will interfere with part j. This question may be answered by common sense or by intensive analysis depending on what is involved and on the experience of the questioner. Analysis is described in the next topic.

The first matrix should be at top level (e.g., the MPM matrix of Figure 3-1). Compatible elements are checked off, and risky elements are expanded.

The expanded matrices are based on a finer partition of the top-level parts. The most useful partition will ordinarily be based on procurement plan. In the final, detailed matrix that orders the more extensive analyses, it is essential to partition antennas separately from their electronics. The MPM vehicle matrix (Figure 3-2) illustrates the extra visibility this approach affords.

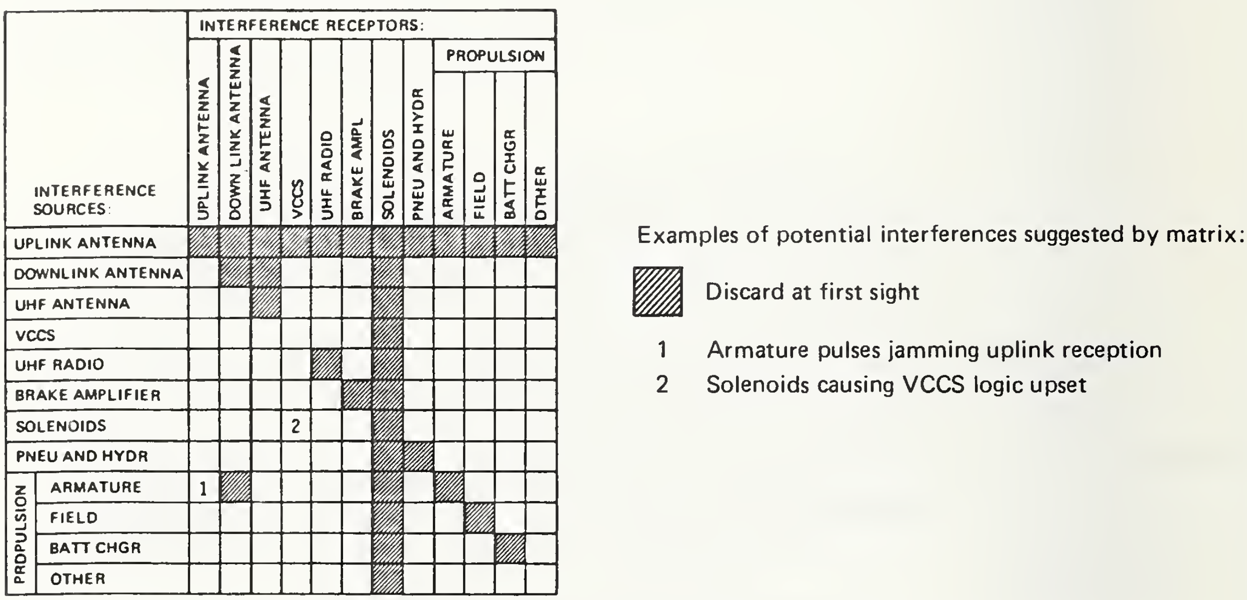

FIGURE 3-2. VEHICLE INTERNAL INTERFERENCE MATRIX

The process just sketched directs attention to all possibilities except multiple-part interference and build-up interference. Where the interaction of two or more parts causes interference that no part alone can cause (e.g., as in heterodyning), the term "multiple-part" is appropriate. Heterodynes can be predicted, but other multiple-part interferences are found by system test. In "build-up" interference the effects of many sources add to produce a net effect that exceeds receptor threshold.

This is the case when, for example, a wide-band instrumentation amplifier picks up so much noise from many sources that the output becomes unusable. Build-up interference is identified from the matrix by adding the effects of a column of elements.

In closing this explanation of the matrix method for risk prediction, note the guideway self-compatibility element (Figure 3-1). Upon expansion this will be found to contain a large number of possible interferences between control loops. Compatibility of these elements is the responsibility of the inductive communication designer and need not be specifically addressed by separate EMC analysis. It is important, early in a project to reach common understanding concerning those areas which will be handled strictly internally as a designer's task and which will be considered as EMC interfaces.

3.3.2 Interference Analysis

Techniques for prediction of interference have developed mainly since 1970, because widespread availability of computer analysis techniques emerged about that time. NASA and the military have increasingly emphasized the potential savings in staving off interference disasters through prediction. Successful models now exist for antenna interaction, for cable coupling, and for circuit spurious responses. Together with organizing and data-recall programs these models have been incorporated into large prediction campaigns (e.g., IEMCAP, SEMCAP, and the like).

Interference models, as distinct from related functional models (e.g., TRAFFIC and WIRANT), tend to suffer from a chronic over-simplification that is the price for extensive iteration capability. Thus, massive prediction efforts tend to be regarded as culling steps, and more sophisticated models are brought to bear on known problems. The interference matrix just described is a culling step.

The following is an outline of the basic electromagnetics of interference. A little understanding can often replace much computer printout.

3.3.2.1 Conditions for Interference

There are three necessary ingredients for interference to occur:

1. sufficient source magnitude relative to receptor threshold,

2. sufficient coupling,

3. sufficient "influence" (similarity of modulation).

The order has meaning because source magnitude may be large enough to cause non-linear coupling (breakdown) and circuit response. Likewise, coupling must be evaluated before "influence". Coupling and influence will now be described.

3.3.2.2 Interference Coupling

Most system internal interference is conveyed by conduction and induction. Radiation enters primarily as the coupling mode from radio transmitting antennas to equipment and to other antennas. Interference in which radiation from boxes and cables affects a receiving antenna located in their far field is rare. The result of all this is that most system internal interference paths can be represented as shared resistance, capacitance, and inductance as well as radiation from radio transmitter fields.

For transit EMI specification development these paths may be conveniently rephrased as follows:

1. conduction via power bus,
2. conduction via cables and ground,
3. cable to cable induction,
4. cable to antenna induction,
5. radio transmitter pickup by box and cable.

These may be modeled with occasional accuracy given copius data. But the essential step is to recognize which paths are worth worrying over.

One aid to recognition is the coupling schematic. For example, consider a schematic of the MPM vehicle and guideway (Figure 3-3). On such a diagram the above five interference paths can be sketched provided that:

1. all common power busses are shown;
2. all cables and ground paths are shown;
3. all antennas are shown;
4. worst case positioning is assumed.

The total interference path from source to receptor may be thought of as a source port, a path, and a receptor port. For example, consider an interference that results from noise currents on the 575-volt power cable coupling into the MPM uplink antenna. Here, the source port may be considered to be the propulsion unit connector and the receptor

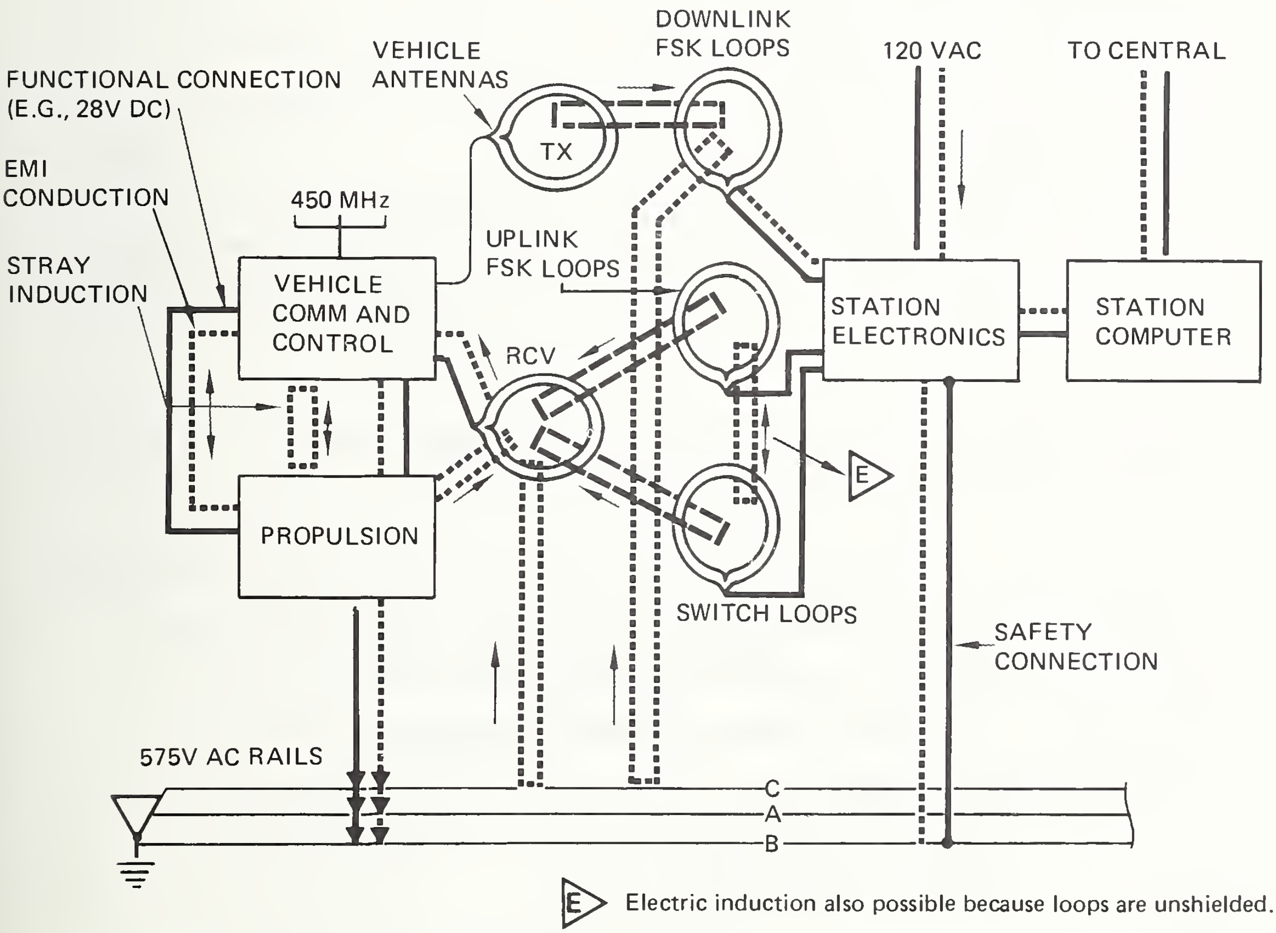

FIGURE 3-3 EMI COUPLING SCHEMATIC

port to be the antenna. The path then becomes conduction down the power cable and induction to the antenna. The ports could be moved further back into their respective equipments. The "port" is the interface between equipment and path.

3.3.2.3 Modulation Influence

Given a source amplitude and a coupling, there is a predicted level of interference signal incident upon the receptor port. The question then becomes: how much is excessive? The answer is seldom simple because the interference signal may exceed the input threshold only to be rejected by later discrimination according to modulation. To illustrate with perhaps the simplest example, consider powerline hum pickup by an audio system. The final discriminator is the human ear. If a low level hum is pure 60 or even 400 Hz, then few individuals would complain of interference. At 1200 Hz, however, minute levels are annoying. In telephone communication the harmonic content of a power line current is termed the "influence factor" of that current. In MPM, to take another example, the VCCS uplink tone receivers respond to cw interference signals according to an amplitude threshold. However, response to impulse interference signals is determined by an amplitude threshold and a repetition rate threshold which combine in a complicated way.

"Influence" describes the time-frequency (algebraic) aspects of interference whereas "coupling" describes the geometric aspects.

Influence can be estimated only in cases for which the incoming modulation is similar to the proper modulation and, as such, have a predictable effect. The unforseen or bizarre combinations of modulation must be put to test in order to discover how much is excessive; otherwise, the worst must be assumed.

3.3.3 MPM Risk Prediction

MPM interference risks were examined in Phase IA and again in Phase

IB. In Phase II only the differences from Phase IB were examined because Phase IB had been proven by a year and a half of service.

3.3.3.1 Phase IB

The Phase IB analysis was performed incrementally before completion of design although the compilation was not released until 1975. These were the predictions:

1. Station electronics rack ac power interface has too many unknowns; special tests required.

2. Power rail noise field (magnetic) due to power collector sliding and bouncing cannot be analyzed.

3. Power rail "armature-controller" noise coupling to vehicle uplink antenna is still being calculated as the system goes into test. (There had been a Phase IA prediction.) Random noise is not a problem.

4. Station electronics circuits vulnerable to lightning are:

    a. Safetone drivers,
    b. FSK drivers,
    c. FSK receiver,
    d. Switchtone receiver.

5. Other circuits vulnerable to lightning are:

    a. VCCS downlink transmitter,
    b. Electrification panel status monitors,
    c. Presence detector receiver, type B.

6. Television camera video noise may be picked up through the camera mount.

7. Speed command to vehicle propulsion controller is vulnerable to noise.

(Of these, only the armature controller noise coupling to the uplink proved to be a problem. In Phase II the television camera ground problem possibility happened at a new station.)

In addition to these specifics, all electronics equipment was assumed to be vulnerable to something and received EMI requirements regardless of specific reason.

The resulting EMI requirements and control plan staved off problems in some areas, missed some, and under-controlled uplink interference. Insofar as the predictions are concerned, the only miss was VCCS vulnerability to transients on signal interfaces.

3.3.3.2 Phase II

The Phase II risk analysis addressed only those differences relative to Phase IB:

1. The vehicle power collector move (forward) could affect uplink noise already considered to be on the border of marginal.

2. New station electronics was not expected to have unique EMI problems but should, nevertheless, receive developmental tests.

3. Vehicle changes were all considered benign but in the aggregate did justify tests for internal compatibility.

4. New station electronics installations were thought to be vulnerable to power rail noise via a ground tie.

5. Central changes were considered benign.

6. Some presence detector reed switches might be activated during power rail faults.

3.3.3.3 Uplink Interference Risk Analysis

As illustration of the foregoing approach to risk prediction (i.e., the matrix, coupling schematic, and influence), analysis of the probability of uplink interference from armature controller pulses is presented in the following discussion.

The MPM analysis begins with the top level matrix (Figure 3.1) in which the partition is one vehicle (X), another vehicle (Y), guideway, station, and community (five parts in all). The four vehicle elements (XX, YY, XY, and YX) all contain armature controller vs. uplink antenna.

Analysis of the possibility of the topic interference proceeds through the three conditions introduced earlier: amplitude, coupling, and influence.

Amplitude - Armature pulses are about 100 amperes, and the uplink thresholds are about one mv (at VCCS). Therefore, coupling and influence must be small if interference is to be avoided.

Coupling - The Phase IB uplink antenna was a coil parallel to the guideway loops. In Phase II the motor current flows in the power collector cables and in the power rails. The resulting power loop is parallel to the guideway loops and to the uplink antenna; this orientation produces greatest coupling. The 100-ampere pulse will produce at least 50 mv (wideband) at VCCS input.

Influence - The interference signal is an impulse train at 360/second with 1/f harmonic amplitudes. The typical receptor is a phase-lock-loop (f_0 = 6 to 30 kHz) followed by a 50 Hz modulation detector. A wide (15 percent of f_0) filter precedes the phase-lock-loop. One of the receivers must respond within 20 ms to modulation loss. The specification on the phase-lock-loop (an integrated circuit) shows that it will lock onto a c.w. signal in less than one ms and that the c.w. threshold referred to VCCS input is one mv. But the response to an impulse is unknown.

The inevitable conclusion from this analysis is two-fold.

1. Interference is probable.

2. Magnitude of interference can be predicted only after determining the impulse response of the phase-lock-loop.

3.4 Prevention Allocation

Interference is most economically prevented by spending prevention effort only where there is risk and, there, spending effectively. That is, effort expended to prevent a suspected interference should be "allocated" to one or more of the hardware units involved and to design measures vs. performance measures. The strategy considerations are fairly complex, at least when treated in general, and are, therefore, taken up in some detail.

3.4.1 Prevention Strategy

Given a risk of interference between two equipments the prevention program may be geared to design its way into the clear, to levy EMI requirements, or to perform developmental compatibility testing. The decision rests mainly on newness. The very old and familiar problem solution will be found in texts and design standards (e.g., diode on relay). The old, but chronic problem solution is an EMI limit levied on the designer. The new problem fraught with uncertainty may best be solved by development tests.

Off-shelf procurements in a developmental or one-time-only program can often be made successfully without the encumbrance of EMI requirements provided that the EMI characteristics are known. System level fixes are often feasible in such a program, whereas compliance of an existing design with an EMI specification can be expensive. Conversely, to accept an existing unknown design can be a mistake. Problems lurk in grounding, bandwidth, internal oscillator beats and in connector pin count restrictions.

3.4.2 Prevention Through Design

Designing to accepted standards will not totally prevent new or chronic problems, but failure to incorporate experience will certainly create problems. For example, dioded relay coils can be successfully packaged with digital circuitry. If interference results, then the cause is design error.

Reliance upon "accepted standards" is a limited aid in the present era of rapid electronics evolution. "Accepted standards" are especially rare in EMI texts because of the time lag between circuit or packaging design developments and EMI texts. Some industry differences are simply alternates. Rack circuit grounding provides an example. Bendix station electronics racks (Phase IA and IB) are not used as a ground plane; the only electrical connection to the rack is for fault return. Boeing station electronics racks (Phase 2) are of military standard quality and furnish an excellent ground plane; this plane is connected as a supplementary circuit return. Both of these practices have merit, and standardization on one or the other is pointless.

3.4.3 Prevention By Specification

Specifications are primarily repositories of experience and as such are particularly suited to the prevention of chronic problems. In addition, specification of quantitative limits on EMI signals and susceptibilities is a sure way to produce action in any situation. EMI limits are a costly tool, however, and should be used with deliberation. Even when the decision has been made to apply a limit the numerical value must be realistic even at the expense of some risk. It has been said that the job of a specification is to prevent eighty percent of the problems. In summary, EMI limits of greater scope or tighter than experience-based limits should be imposed only after careful consideration. The purpose of this topic is to supply some ideas for that consideration.

Creation of an EMI limit consists of selecting an interface and values. First, the interface question will be considered.

3.4.3.1 EMI Interfaces

For EMI purposes an equipment has an envelope interface, a cable interface and an antenna interface.

Envelope - Choose so that the natural RF barrier (e.g., metal chassis) lies entirely within the interface envelope. At contact interfaces, such as mounts, it is necessary to specify whether electrical contact is to be desired or avoided.

Cable - Include the cable in the interface definition to ensure that the cable design is included in the EMI test of one of the interfacing equipments.

Antenna - The interface choice is between the field and the feed point. Whereas the feed point is conveniently simple and specific, the field is the better choice for fostering complementary design of the antenna and receiver system.

In the case of MPM the uplink antenna interface was originally chosen by Bendix to be in the field. Later, the interface was officially moved to the receiver input (practically equivalent to antenna feed), a more practical location. For EMI purposes the field point had advantages, and in looking back both points should have remained in use.

3.4.3.2 EMI Limit Values

A potential interference can be prevented by suppressing the spurious tendencies of source and receptor, or, neither one being at fault, by decoupling (Figure 3-4). EMI limits for equipment address the spurious tendencies. Decoupling is addressed in the installation design.

	PROPER EMISSION	SPURIOUS EMISSION
PROPER RECEPTIVITY	— DECOUPLE —	SUPPRESS DECOUPLE —
SPURIOUS RECEPTIVITY	— DECOUPLE DESENSITIZE	SUPPRESS DECOUPLE DESENSITIZE

FIGURE 3-4 EMI PREVENTION OPTIONS

Figure (3-4) shows that only in the double-spurious case does there exist the possibility of trading source suppression for receiver desensitization. In the other two cases involving a spurious property, the only mitigation of need to limit the spurious property is by decoupling. For example, in the case of the MPM vehicle armature controller vs. uplink antenna, the noise is in-band to the antenna. All that can be done is to suppress the source and try to decouple the antenna from the power rail.

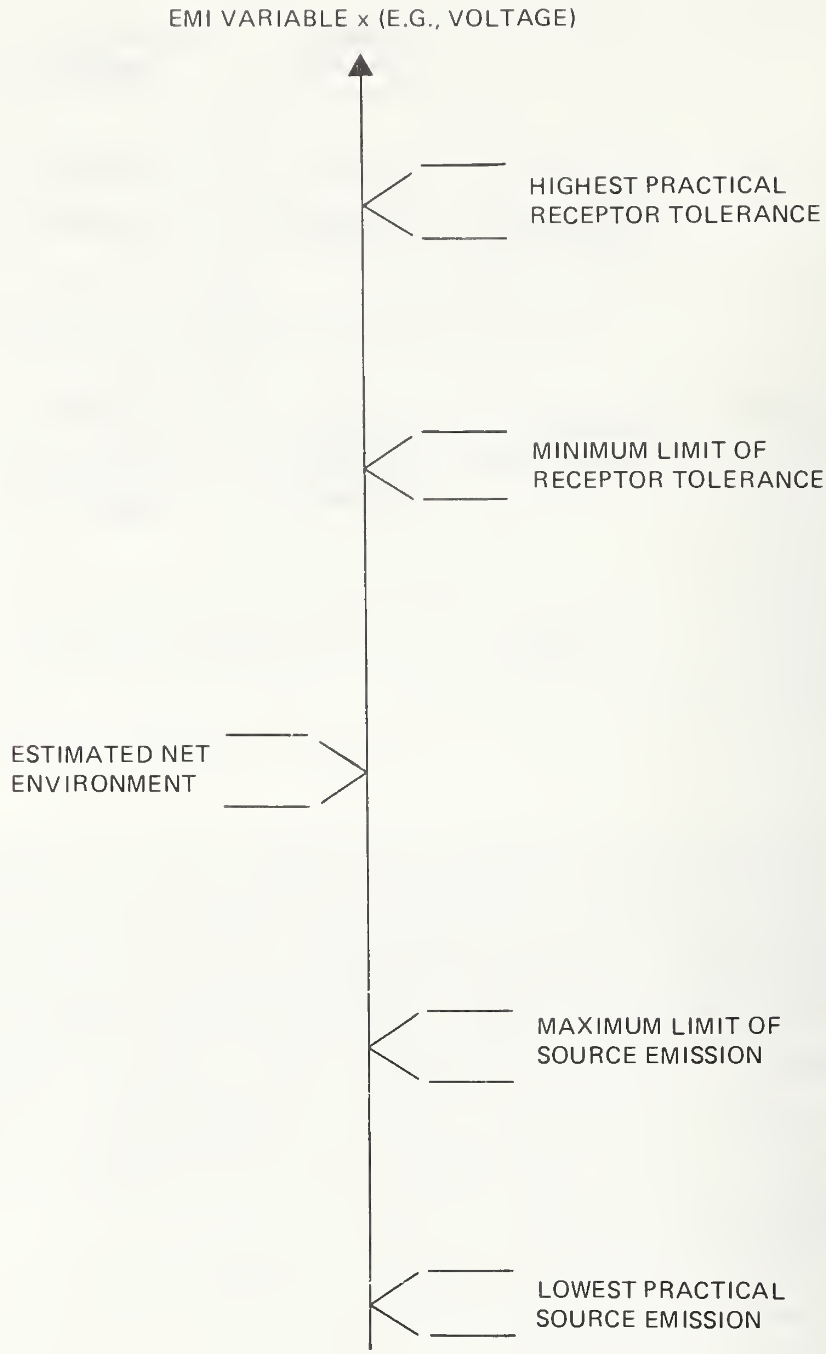

FIGURE 3-5 EMI LIMIT BAROMETER

The process of selecting limits can be summarized in a barometer diagram (Figure 3-5). For an EMI variable, such as the magnetic noise field at the MPM uplink antenna, for example, five parametric values of the variable are shown. Source and receptor each have two: a potential ideal (but practical) level of performance and the chosen limit level. In the middle is the expected environment, the sum of all things present. This may be unalterable. Also, one or the other limit levels may be unalterable (if functional). The barometer implies an estimate of decoupling available (MIL-STD-461 assumes no decoupling). To get the two limits, the potentials, the constraints, and the environment are assessed; then a maximum limit for the source and a minimum limit for the receptor are chosen. These limits are the allocation of the subject risk to the participating equipments.

This process is difficult because, typically, most of the input data is unavailable early in a program. The largest uncertainty, noted earlier, is the modulation influence of potential source upon potential receptor. Mathmatical models to assist prediction of decoupling and modulation influence have become a current standing challenge. Because of the difficulty in selecting practical limits, most programs accept the most nearly appropriate consensus standard - even if it represents experience that does not apply.

The simplest EMI variable to specify is dc powerline noise. There is no decoupling; source emission equals receptor input. The environmental level is the sum of source "ripple" and load generated "ripple." In racked electronics the secondary power supplies typically emit 0.1 percent ripple and the bus nets about 0.3 percent (for a "quiet" bus) to 10 percent (for a "noisy" bus).

Power bus EMI quality can be established at any level that is coordinated. However, if very low ripple is desired (0.3 percent) then a ground plane becomes necessary. Power quality standards like MIL-STD-704 for airplane power do not appear to have emerged in the areas of wayside electronics and vehicle electronics. The MPM vehicle dc bus is designed at 5 percent ripple; (it is better than that.) This has proven to be a good choise. No bus filters are used, yet power quality is adequate. The bus is fed by a "battery charger" at 20-foot distance and by a battery at 3-foot distance. The three electronic loads each contain regulation and filtering.

MIL-STD-461 Notice 3 increased the allowable level of noise emission into a powerline by 10 dB over MIL-STD-461 basic. Notice 3 and the basic standard are alternates. Even with this flexibility the standard may not suit a particular transit application because the standard originates in airplane practice where dc power is generated in a certain way (T-R units, unregulated, fed by regulated ac power).

3.4.3.3 Continuous Wave Interference

Prevention of c.w. interference is included in the foregoing discussions on limit-setting. However, c.w. interferences do not usually add; thus, the environment parameter on the noise barometer may not apply for c.w.

A frequency-use histogram is more appropriate to c.w. prevention than is the amplitude-only barometer tool. All oscillator frequencies, including those of switching regulators, converters, clocks and carriers are plotted in histogram form. All receiver frequencies and the associated images (if superheterodyne) are plotted in histogram form. The point of reference for amplitude is taken at the receiver antenna of concern. Units of amplitude are volts/m for rod antennas and amps/m for loops. The completed histogram is reviewed for first and second order heterodyne interference. Sometimes it is advisable to essay a third order "beat" analysis by hand. Higher order "beat" interference does not occur in civil systems.

3.4.4 Developmental Compatibility Testing

If the outcome of risk prediction is high probability of interference combined with uncertainty, then a developmental compatibility test may be justified. An example would be the MPM armature controller vs. uplink phase-lock-loop receiver. In a "developmental compatibility" test prototypes of the probably incompatible pair are integrated with worst-case (i.e., close) coupling. This test reveals the amount of decoupling necessary for compatible operation. Such a test is essentially a measurement of the "modulation influence" of one equipment upon the other. (See subsection 3.3.2.3.)

3.4.5 MPM Uplink Interference Prevention Allocation

The identified risk was SCR pulses from the armature controller coupling from the power rail to the uplink (loop) antenna by mutual inductance and there causing obstruction of uplink communications.

The prevention allocation was a tolerance requirement on the VCCS receivers (seven are fed by one antenna) and a powerline conducted emission limit on the propulsion unit.

The VCCS tolerance requirement was a noise amplitude density spectrum at receiver input. The idea was sound, but insufficient test requirements were included, and the implied test was not accomplished. Also, the impulse PRF was not stated in the requirement. The actual propulsion noise character should have been specified.

The propulsion powerline conducted emission limit was taken to be the existing level of a prototype. This was an error given the amount of decoupling provided by the antenna design originally proposed. However, nothing practical would have been gained by asking for more suppression. The conclusion drawn later was that control by specification of EMI limits was not a feasible control in this case. Developmental compatibility testing would have saved time in the end.

3.5 Specification Formulation

The form of a quantitative EMI requirement should, if feasible, follow a consensus model such as MIL-STD-461, and this transition from program-peculiar risk analysis to "standard" form involves some information not yet introduced. A discussion of EMI variables is followed by an index of MIL-STD-461 tests and by comment.

3.5.1 EMI Variables

An "EMI" variable description has a "mathmatical" part and a "physical" part:

Mathmatical Part - examples

- Amplitude (any physical variable)
- Amplitude in stated bandwidth
- Amplitude density (normalized bandwidth)
- Modulation description;

Physical Part - examples

- Conduction mode (common, normal) volts, amperes
- Induction field volts/m and amps/m
- Wave field (far field) volts/m or amps/m.

A typical EMI variable is volts/m/mHz,the variable describing a broadband electric field. The mathmatical part is the "per megahertz" and the physical part is the "volts per meter".

The important "mathmatical" choice is the bandwidth of the measurement. The foolproof rule is to measure with the same bandwidth as that of the receptor at risk. Beware of amplitude density (per megahertz) data. This variable is obtained with arbitrary bandwidth and means something only when the broadband impulse repetition rate is low compared with that arbitrary (unspecified, and often unreported) bandwidth.

Amplitude density was introduced as a measure of the tendency of ignition noise to interfere with a communications receiver. Use this variable only in analogous situations.

The mathmatical portion of any variable could in principle be described either by time or frequency domain measurement. The choice should depend solely upon the nature of the receptor at risk. This is merely a restatement of the bandwidth rule just noted. Actually, the distinction between time and frequency domain measurements is fading as oscilloscopes acquire bandwidth selectors and spectrum analysers replace communication-style receivers.

Choice of the physical variable depends on convenience of measurement. Only two variables are needed to describe the physics of a signal. Conduction and induction variables are equivalent so that one can sometimes be traded for the other. For example, the magnetic field of a powercord to a device can be measured directly with an antenna (US preference) or indirectly with a current probe clamped around the powercord (European preference).

3.5.2 EMI Limits

Subject to appropriate choice of variable the EMI requirement can be phased in terms of MIL-STD-461 tests (Figure 3-6). Each risk variable

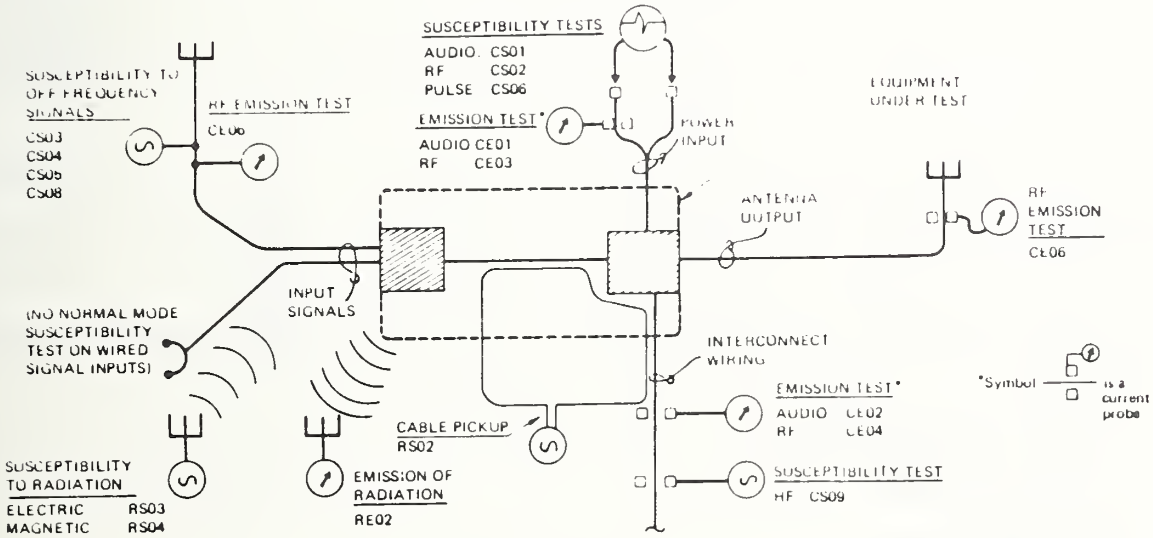

FIGURE 3-6. MIL-STD-461 TESTS

has a counterpart pair of tests, one for the potential source and one for the potential receptor of interference (Table 3-3).

TABLE 3-3. MIL-STD-461 TEST INDEX

Risk Variable Subsection 3.3.2.2	MIL-STD-461 Source Test	Receptor Test
Power bus conduction		
Audio frequencies	CE01	CS01
Radio frequencies	CE03	CS02
Spike	(1)	CS06
General Cable Conduction		
Audio Frequencies	CE02 (2)	(none)
Radio frequencies	CE04 (2)	CS09
Cable-Cable Induction		
Magnetic	CE02 (3)	RS02
Electric	(none)	(none)
Cable to Antenna Induction		
Magnetic	CE02 (3) CE04 (3) RE01 or RE04	RS01 or RS02
Electric	RE02	RS03
Antenna to Antenna	CE06	CS03 CS04 CS05

NOTES:

(1) No time domain test

(2) Normal mode

(3) Common mode

Detailed variable description in each of these MIL-STD-461 tests is standardized and should be questioned as described above as to whether it is valid for the receptor (or receptors) at risk.

Numerical value of the limit for each test comes from the barometer exercise (previously discussed) but can be modified to include broader considerations. The essential step in modifying the barometer exercise is to return to the interference matrix which lists all sources threatening a receptor and all receptors threatened by a source. By considering these totals the "environment" parameters can be validated so that they better support the final choice of source maximum limit and receptor minimum limit.

There are, for example, four sources of magnetic field noise at the MPM uplink antenna (units are Teslas rms, 1-kHz bandwidth):

From power rail armature controller pulses (PRF=360): 1×10^{-6}

From power rail collector brush arcing (PRF Sporadic): 3×10^{-6}

From loops, carrier sidebands (PRF=100) : 1×10^{-7}

From specified environment (corona) : 6×10^{-13}.

Given this information it follows that armature noise should, if feasible, be reduced to about one-third (100/360) of the level of the carrier sidebands and that further reduction is wasted effort.

Part of the broadening of the environmental base of limit determination is recognition of future use. A hardware unit or subsystem created for special use might later come into general use. If this is foreseen, then EMC requirements should be extended accordingly. Until a consensus standard for transit EMC comes along, the simplest approach in such a case is to require MIL-STD-461A, Notice 3, Class A for vehicle and Class B-3 for wayside.

3.5.3 MIL-STD-461

This tri-service consensus standard has three versions: a basic, an Army (Notice 4), and an Air Force (Notice 3). The latter is the best for transit use. Standard 461 Notice 3 leaves ample room for substitution of program-special numbers, modes and constraints. Notice 3 is based on assumption of higher environmental levels than in the basic standard.

3.5.4 Problems in Setting Receptor Test Requirement

Tests of the susceptibility of a receptor are more difficult than source emission tests because knowledge of the receptor's inner workings is essential to proper adjustment of the sending apparatus. Chronic problem areas are modulation and mode.

The "threat" signal impressed upon a sample should mimic the real environment in which it will be installed. Most EMI susceptibility tests are conducted in the frequency domain with arbitrary modulation regardless of need because truly flexible EMI environmental simulators still are not available. As a result of their lack, the "chattering" relay has been pressed into service by concerned designers. This is now a standard EMI source in some industries.

The choice of mode in which a sample is operated while being subjected to an environment presents a problem because the ideal mode seldom can be found. Ideally, a guasi-static mode is desirable which not only exhibits all potential susceptibilities but which also can be maintained for tens of minutes, the time span required for the environmental simulator to be sequenced through its modes. Often, the sample can be validly tested only by running it through an operational sequence. For instance, in MPM a sneak path caused a problem to an A to D converter only if energized while the converter was being switched on.

3.5.5 Duplication of EMI/Power Quality Requirements

EMC conducted emission requirements must be cross-referenced with power design requirements in order to avoid double-specification, inconsistency, and omission. The composite set of requirements for a secondary DC bus illustrates the scope of bus requirements as well as the duplicity problem (Table 3-4).

Table 3-4. POWER QUALITY REQUIREMENTS

Variable	Specification Section
1. Regulation (to 1000 Hz)	Design
2. Source generated periodic noise:	
a) 1 to 150 kHz	Design
b) 20 kHz and up	EMC
3. Load generated periodic noise	EMC
4. Source generated transients	Design
5. Load generated transients	EMC
6. Load inrush current	Design
7. Load tolerance of periodic noise:	
a) Up to 150 kHz	Design
b) 30 Hz and higher	EMC
8. Load tolerance of transients	EMC and Design
9. Bus impedance	Design

3.5.6 MPM EMC Requirements

In the beginning, Phase IA, the current military EMI standard, MIL-STD-461, was listed as a guide. During Phase IA Bendix developed the station electronics and the vehicle communication and control system (VCCS) while Boeing developed the vehicle electrical system. Only the propulsion system received an EMI test, and this was a carryover from another program. At the start of Phase IB, the cost and need of requiring MIL-STD-461 compliance were considered. The result was a tailored version which reflected the minor role of radio communication devices in the MPM system (Table 3-5).

TABLE 3-5. PHASE IB EMI REQUIREMENTS

ITEM	RS-NBE	RS-BBE	RS-BBH	CS-PL	RE-NBE	CE-PL
C&CS						
Central Computers		X		X		
Oper. Consoles	X	X	X	X		X
Mimic Assembly		X		X		
CCTV Camera S/S	X	X	X	X		X
RF Transceivers	X			X		
Station Computers		X		X		
Station Electronics		X	X	X	X	
Fare Collector		X	X	X		
Fare Card Dispenser		X		X		
Vehicle						
VCCS						
Brake Servo Amplifier						
Propulsion System						
Door Operator						

LEGEND:
RS-NBE = Radiated Susceptibility - Narrowband Electric Field
RS-BBE = Radiated Susceptibility - Broadband Electric Field
RS-BBH = Radiated Susceptibility - Broadband Magnetic Field
CS-PL = Conducted Susceptibility - Powerline
RE-NBE = Radiated Emission - Narrowband Electric Field
RE-BBE = Radiated Emission - Broadband Electric Field
CE-PL = Conducted Emission - Powerline

During Phase II, EMI requirements for the redesigned items were largely copied from Phase IB on the assumption that the internal environment was going to be the same as before. Station Electronics internal test requirements were added to search for internal compatibility (not done in Phase I). New transient susceptibility requirements were developed for the new fare gate.

Phase II power EMI requirements, collected from functional documents and the EMI control plan, are listed in Table 3-6.

Table 3-6. MPM POWER BUS NOISE REQUIREMENTS

VEHICLE

A. Propulsion power, 575 Vac @ 1000 A, 3 phase.
 - o Source generated noise: No requirement
 - o Load generated noise: 20 to 40 dB above MIL-STD-461 CE03

B. 28 Vdc (battery bus)
 - o Source Ripple: 5%
 - o Transient tolerance: 56 volts
 - o Load generated noise: No requirements on any load (VCCS, brake amplifier, radio, or propulsion system)

C. Tertiary busses within propulsion system and vehicle controller are not addressed by the system EMC specification.

STATION ELECTRONICS

A. Housekeeping power, 575 Vac, three phase.
 - o No EMC requirements

B. Uninterruptable 120 Vac single phase to racks.
 - o Source generated noise: No requirement
 - o Load generated noise: No requirements
 - o Transient tolerance: 100 volts

C. Rack dc Busses (5, $\pm$15, $\pm$30 Vdc)
 - o Source generated ripple: 0.1%
 - o Load generated ripple: No requirement
 - o Load tolerance of ripple: 0.3%

3.6 EMC Control Plan

The present day "EMC Control Plan" is a military innovation (MIL-E 6051) which in scope repeats the documents that build a system. Consequently, it often happens that the control plan is no more than a communication between the EMC staffs of contractor and acquiring authority. A prominent example of redundancy is the duplication between the "System Test Plan" and the test plan part of the "EMC Control Plan." The result of the redundancy is that the chief role of the control plan may be to function as a work plan for the EMC staff. At any rate, the following report on the MPM EMC Control Plan stresses test planning and design assurance, the watchdog task.

Some control plans include the governing EMI specification (MPM's does). Whether or not the plan and the specificaton are so combined is not of general interest. The advantage is one less document. The disadvantage is confusion over the contractual status of the combined document.

Specification MIL-E-6051 requires that a control plan contain a complicated mixture of information and planning. (See Table 3-7.)

Table 3-7. MIL-E-6051 EMC CONTROL PLAN

1. Resources and responsibilities
2. Plan for compatibility of conventional equipment designs
3. Plan for compatiblity of innovative equipment designs
4. Plan for compatibility of off-shelf equipment designs
5. Data on antenna coupling
6. Plan for shielding and routing cables
7. Study results on corrosion problems with bonding
8. Design criteria, test plan and assurance plan for lightning protection
9. Design criteria, test plan and assurance plan for precipitation static suppression
10. Design criteria for power bus spike protection
11. Design criteria for bonding and grounding
12. Design criteria for spectrum-utilizing circuitry

13. Methods for reviewing designs and for coordinating with vendors

14. "Criticality category, degradation criteria and safety margins for equipment"

15. Schedule

In addition, the MIL-E-6051 Control Plan shall include establishment of an "EMC board."

This is a valuable checklist. In the suggested outline for a Transit EMC Control Plan (Table 3-8), the subject of design criteria is omitted. The designers all have their own guide books, and it is just as well for the EMC staff to keep their guide books in reserve. Each category in the suggested Transit EMC Control Plan outline (Table 3-8) is explained.

Table 3-8 TRANSIT EMC CONTROL PLAN

1. Design Plan - Addresses Risks (e.g., routing plan)

2. EMI Requirements - Quantitative EMI Limits

3. EMC Requirements - MIL-E-6051 Test Requirements

4. Procurement Plan - For Accepting Procurements

5. Sneak Circuit Analysis Plan

6. Test Plan - Developmental
   Compliance
   Integration
   System Level

7. Design Assurance Plan - Review of Drawings

Design Plan

Based on the risk prediction the control plan should state either specific risk reduction measures or plans for developing these measures. This material ranges from considerations about the presence or absence of diodes on relays to plans for realizing a system ground plane.

EMI Requirements

The EMI requirements are applied to individual electrical equipments according to the prevention allocation study.

EMC Requirements

This section should define criticality categories, degradation criteria, and safety (EMC) margins for equipment. Modes tested for compatibility should also be included.

Procurement Plan

Off-shelf, developmental and conventional designs that are procured are here considered in turn and assigned a verification scheme -- accept as is, information test, breadboard test, compliance test, or test after accceptance.

Sneak Circuit Analysis Plan

This plan provides for tracing out unwanted paths involving opposing power sources, switched grounds, partial power, and misleading switch position labels.

Test Plan

The test plan should address four test categories:

a. Developmental compatibility tests in which a pair of prototypes is integrated

b. Equipment breadboard and compliance tests per above EMI requirements

c. Integration

d. System tests.

Design Assurance Plan

EMC approval of drawings and documents that build hardware is analogous to reliability and maintainability approval and should include:

Documents:

All electrical-electronic procurements
All equipment and subsystem specifications
Test plans;

Drawings:

Circuit schematics
Circuit card layouts
Chassis assemblies
Wiring diagrams
Installation diagrams.

This listing permits large gaps in system review wherever wire lists are used. It is, therefore, essential to create schematics to plug these gaps. The schematics are also needed for sneak circuit analysis.

Completeness is a challenging aspect of design assurance because the whole is not manifest until actually built. In the VCCS for example, a ground loop became bundled with sensitive wiring. This bundling was not apparent in any released drawing because the essential data for example, a ground loop became bundled with sensitive wiring. This bundling was not apparent in any released drawing because the essential data were buried in a wire list. One device to ensure appropriate design, therefore, is to draw total schematics early.

Completeness of drawing sign-off can be achieved through the use of drawing "trees." Drawing sign-off by EMC staff is not a universally favored assurance device. Selective approval can avoid delay while ensuring review of high risk designs for particular EMI aspects. The best plan, therefore, is to identify at the outset those drawing releases which must bear EMC staff approval.

3.6.1 MPM Control Plan

The MPM Control Plan for the second phase contained:

- The EMI specification
- Risk analysis results
- Drawing sign-off plan
- Analysis plan
- Test plan (developmental and qualifying).

This was carried out as planned. Next, the MPM Test Plan is described. (See Table 3-9.)

TABLE 3-9. MPM TEST PLANS

Equipment	Planned Test
Station Electronics:	
Phase IB	(Bendix: none) FCC emission test at the STTF
Phase II Cards (redesign)	None
Phase II Racks & Cables	SIL test of each new or modified system
Phase II Station	Installation test of each new or modified station
Vehicle:	
Power Collector, Phase II	Development tests, laboratory and at the STTF
VCCS Uplink Receiver	None
VCCS (except receiver)	
Phase IA	None
Phase IB (redesign)	Compliance Test
Phase II (mod)	Compliance by similarity
Brake Amplifier	
Phase IB	Compliance Test
Phase II (new)	Compliance Test
Propulsion	
Phase IB	Prototype test only
Phase II (mod)	Compliance by similarity
Radio	None
Vehicle	
Phase IB	Compliance Test at STTF
Phase II (mod)	Compliance Test at STTF

The main difference between Phase IB and Phase II EMC testing was the station electronics test in the System Integration Laboratory. The rationale was that extensive changes had been made in important circuit areas.

The prime Phase II risk was uplink noise jamming due to power rail/collector induction; hence, this was tested thoroughly in the laboratory and on the test track.

The bulk of factory testing addressed the redesigned station electronics at the qualifying stage (noted above). A few circuit breadboard EMI tests were undertaken on the initiative of individual designers. This balance was in keeping with the conventional nature of the new designs. The test plan was adequate except for the omission of a propulsion -VCCS prototype compatibility test.

4.0 MPM ASSESSMENT

A design can be assessed both for innate quality and for adequacy:

Quality Questions:

Is it textbook good?
Is it consistent?

Adequacy Questions:

Will it work here?
Will it work there?

Quality questions have been answered in MPM by analyzing the design. Adequacy questions were the goal of the MPM test program. Both analysis and test were influenced by the original Phase II risk prediction as reported in the control plan and have been carried out in accord with plan.

4.1 Design Analysis

4.1.1 Methodology

Design analysis was a repeat of risk analysis but accomplished in greater detail. The three conditions for interference translate to assessment tasks as follows:

Amplitude ⟶ Basic design

Containment ⟶ Packaging

Modulation ⟶ Schematics.

Basic design scrutiny covered component types, voltage and impedance level. Most of this work was performed during Phase IB.

Packaging scrutiny focussed on return path tracing and also included power bypassing. At each connector these questions were asked:

1. For each pin, where is the return for the current, or where is the reference for the voltage?

2. With the complementary pin and path identified, is the interface isolated?

3. Is the impedance sharing acceptable?

4. If filtered, can EMI sneak by the filter?

5. What is the common mode rejection?

In station electronics the circuit card rather than the circuit drawer is considered the basic chassis. The above questioning was applied down to card connector level. Presence or absence of shields had long since been decided; in assessment the terminations were scrutinized with respect to the following:

1. Inner shields tied to circuit reference?

2. Outer shields tied to system ground?

3. Intermediate connectors: must not join (i.e. connect to common pin) inner shields of incompatible circuits.

Cabled circuitry is responsible for perhaps three quarters of all interference in systems not predominantly composed of antennas because cabled circuits are larger and, thus, have larger induction fields than unit circuitry. The MPM Phase IB most serious interference problem, excessive safetone level in the "off" state, was a cable problem.

The crucial aspect of cable assessment is that it be accomplished (i.e., that each circuit which is completed via cabling be given the same attention as unit circuits receive). This is an irksome job when the cable exists only in a wirelist. For example, the VCCS ground loop problem (previously discussed) was camouflaged by detail.

Schematic scrutiny posed questions of time and frequency:

1. Digital receivers gated?

2. Discrete circuits enabled for minimum time?

3. Receiver bandwidth a minimum?

4. Response time no faster than necessary?

5. Modulation chosen with regard to environment?

In MPM there is a coincidence between the speedtone tracer modulation and "switch right" modulation. Containment is acceptable, as are the consequences of crosstalk. However, separate modulation frequencies would have been an easier choice to work with.

This "time-frequency" questioning was done mainly by the designers with assistance by the EMC staff.

Drawing sign-offs proved to be invaluable mainly because they brought staff and project into closer communication than otherwise would have been the case. A major problem which should be corrected in any subsequent project, existed, however. Certain drawings, namely printed circuit layouts and wire lists, were on the sign-off list just as were all other "make" drawings. The problem was that review of these portions of a design necessitated use of supporting schematics which either were not slated for issue (wire lists) or were to be were released later (layouts). The answer is to include in the control plan the steps needed to make schematics available.

4.1.2 Phase II Vehicle and Guideway Design Scrutiny

Major Phase II differences of possible EMC effect were:

1. Power collector moved forward, closer to uplink antenna;
2. Power collector no longer retractable;
3. VCCS new power supply and greatly enlarged fault reporting;
4. Redesigned brake amplifier;
5. Power rail redesign;
6. Added substation in old guideway.

The assessment was that uplink interference would increase because of the power collector move in spite of laboratory tests optimizing the new route. No other Phase II problems were identified.

This assessment proved to be pessimistic as to uplink noise and optimistic as to VCCS changes. Uplink noise did not increase.

Two late changes to the VCCS proved to be necessary in order to correct:

1. Logic upset due to transients entering on an un-isolated, unbalanced, 5-volt radio control line.
2. A sneak circuit from incoming tachometer voltage to "power-on-reset" during power turn-on.

The control line design peculiarity had been spotted, but because it had always been there, no change action had been taken. Evidently, the addition of the extra fault status inputs nudged the problem into the open.

The sneak circuit would probably have been found had the Phase IB sneak circuit analysis been repeated on the changes. The change that enabled the sneak to surface was a new VCCS power supply. Its 5-volt output changes to a high impedance state when de-energized. Thus, any voltage fed back from a load, here a tachometer line receiver, now generated a false bus voltage (about 2.5 volts). This, of itself, was no problem, but the VCCS has a "power-on-resetter" that triggers on the turn-on step form to generate a logic reset. The sneak so reduced the step form as to inhibit the reset.

It can be concluded that scrutiny can be nearsighted. A cable transient susceptibility test was in order, and a partial-power analysis for sneaks should have been conducted.

4.1.3 Phase II Station and Central Design Scrutiny

Major Phase II differences of possible EMC effect were:

1. New rack grounding,
2. Redesigned uplink loop drivers and FSK transmitters,
3. Incorporation of microprocessor in the CAS,
4. Enlargement of control console (added stations),
5. New fare gate.

The assessment of C&CS station racks and the central consoles concluded that no EMC problems should arise. In major matters this was the case, but minor problems did arise. For instance, the fare gate had to be modified to eliminate an infrequent logic upset problem, and Towers television was noisy.

However, the assessment cannot be totally credited with correct prediction of the success of the new station electronics. Four EMI problems were disclosed by functional tests in the System Integration Laboratory.

Of these, two could have been expected to be caught by scrutiny while two others (pulse edge crosstalk) were of the obscure kind that digital designers shake out by test.

The television horizontal bands of ripple (problem which developed at Towers Station) had been predicted back in Phase IB and was missed in the current scrutiny. A video coax which was double-grounded over a distance of 100 feet was the cause of this problem.

4.2 Test Program and Results

This section describes the EMC assurance tests conducted over the time span of the MPM program.

4.2.1 Phase IB Test Program

The Phase IB program was an integration of parts previously developed by associate contractors. The Phase IB EMC test plan, therefore, addressed an existing station electronics system and an existing propulsion system.

Tests in the EMC Control Plan included unit compliance for major vehicle items, vehicle power bus noise and FCC compliance tests at the Surface Transportation Test Facility (STTF), and a Morgantown system test. In the actual test program the STTF test was expanded to full-scale system compatibility.

Between the STTF test and final Morgantown test many diagnostic tests on uplink interference were performed at the STTF and, later, at Morgantown; these tests addressed safetone and stoptone problems which had arisen at Morgantown. The Morgantown system test then successfully demonstrated 6 dB margin for critical circuits.

In assessment the above program with the important exception of development tests on the high risk uplink noise situation was adequate.

STTF tests are discussed in more detail in subsequent sections.

4.2.2 Phase II Test Program

The Phase II program EMC tests were as follows:

Program Hardware	EMC Tests
New Power Rail and Collector	Development tests in laboratory and at STTF.
New and Modified Station Electronics	Compliance test of four sets of integrated racks prior to shipping, and of four completed stations at Morgantown (I&C/O tests).
Phase II Vehicle	Prototype overall test at STTF.
Modified VCCS	No test planned. (Diagnostic tests added later.)
New Brake Amplifier	Compliance test on early production model.
Phase II System	Compatibility margin test.

In assessment this EMC testing except for the lack of VCCS testing (discussed in Section 4.2.4) was necessary and sufficient.

4.2.3 VCCS, Phase IB

The planned Phase IB VCCS compliance test was a straight-forward carrying out of the system EMI specification:

powerline susceptibility,

powerline emission,

radio wave susceptibility.

All tests were successfully completed.

Soon after deployment at Morgantown the VCCS proved subject to uplink jamming by power rail impulse noise.

The VCCS had been designed to tolerate a stated impulse noise spectrum (VCCS Spec., Figure 5). However, the tolerance had not been tested. Therefore, it was not until the system problem became manifest that the basic incompatibility between propulsion and uplink became known.

The assessment was that a high risk case like propulsion vs. uplink warranted more attention during development than was in fact given. MIL-STD-461 compliance would not have sufficed; MIL-STD-461 does not require in-band noise threshold tests at a receiver input.

4.2.4 VCCS, Phase II

Phase II - Phase IB design changes were judged sufficiently minor that no EMI test was necessary. Areas changed were the power supply and fault status logic. The new power supply was a vendor catalog design. The fault status change was an increase in the number of circuits.

The acceptance-by-similarity proved valid regarding the old uplink noise problem.

A sneak circuit developed between the new power supply and the tachometer input. A transient susceptibility problem developed with an unchanged interface circuit (an "arming line"). This could have been nudged into manifestation by internal bundling changes related to the increased fault status circuitry.

The VCCS test assessment for Phase II was that acceptance-by-similarity was valid for major risk but invalid for details. The decision at CDR to produce the Phase II VCCS was valid. But it was invalid to assume then that no EMC problems would occur. This experience led to the conclusion that a power supply change warrants a sneak circuit analysis and that a bundling change (in digital-discrete circuitry) warrants a transient susceptibility test (like that of MIL-STD-461 RS02).

4.2.5 Phase II Station Electronics Test Program

System Integration Laboratory (SIL) tests of integrated station electronics were added in the second and final draft of the EMC Control Plan. The added tests were productive.

SIL tests of integrated station electronics consisted of:

1. bonding,
2. ground potential drops,
3. power supply ripple,
4. transient susceptibility: conducted AC and cable pickup.

The approach in devising this plan was to assume internal details to be in the scope of functional tests and to aim the EMC test at the environment. The tests were inexpensive, brief (about 24 hours per station), and provocative (eliciting both confidence and concern). The concern was caused by discovery of high levels of power supply ripple without knowledge of how much could be tolerated (concern assuaged by noting Phase IB experience with higher levels).

The SIL EMC tests:

1. found +5 and +24-volt bus ripples well above target in Phase IB design areas;

2. found a defective power supply;

3. found an EMC design problem (a shared impedance);

4. proved the adequacy of rack bonding;

5. proved the "ruggedness" of interconnecting cabling.

The SIL functional tests found four EMC problems:

1. noise resetting a flip-flop,

2. noise setting a flip-flop,

3. bus ripple causing beats in a phase lock loop,

4. positive feedback oscillation due to shared power return.

The major effort expended in surveying bus ripple would have been more worthwhile if supplemented concurrently with determination of margin. The designers at first wanted 0.1 percent ripple. But when one +5 volt bus reached 16 percent ripple (later remedied) the circuits continued to function normally. In another example, the bus ripple that caused phase lock loop beats was within a pre-selected limit; but there was no margin.

The SIL EMC tests were worthwhile primarily because they reduced the possibilities for trouble in the field. Other programs could also benefit from this kind of test, the more so if power bus quality margin be included.

4.2.6 Propulsion Test Assessment

The MPM propulsion system had been developed for another transit vehicle (AirTrans) and modified only slightly for MPM use. As an economy measure the original EMI data were not retaken. Armature controller impulse noise at the three phase ac input exceeds the MIL-STD-461 limit by 40 dB at the MPM safetone frequency. The system has internal suppression and filtering, is completely shielded, and has filters on all wire penetrations of the shield.

Installed in the MPM vehicle the system performed compatibly at the STTF. However, at Morgantown the armature controller noise jammed an uplink communication channel. An attempt to get the propulsion emissions remeasured was overruled on cost. Before long, the problem was corrected by redesigning the uplink antenna.

During Phase IB the feedthrough filters on Phases A and C of the ac input began to fail due to a corona problem. At the outset of Phase II these two filters were deleted following EMC tests on a prototype vehicle. Also at this time the EMI gasket in the access cover of the propulsion enclosure (there was a corrosion problem) was deleted following EMC tests on the same prototype vehicle. Compatibility was checked in general and also specifically at 10 kHz, 130 kHz and 450 MHz. The effect of the filter and gasket deletions should have been an increase in conducted emission above 20 MHz (upper limit of remaining ac can-type filters) and an increase in radiation at VHF and higher frequencies. It was predicted and borne out that the MPM vehicle was not susceptible to such increases. Uplink frequencies are 6 to 130 kHz.

At the time of the filter and gasket deletions the Phase II vehicle was in its prototype stage. No armature contoller interference with uplink communications was being experienced at the STTF.

But would there be interference at Morgantown? This was of concern because in Phase IB the uplink problem was not manifest until vehicle operation at Morgantown. The concern was not lessened by the filter and gasket deletions.

Tests, telephone calls, and weekly status meetings led to a decision to continue vehicle production without any additional EMI measures. STTF tests had indicated an uplink impulse noise margin of about 17 dB. It was hoped that at least 6 dB would remain during multiple vehicle operations at Morgantown. There were many unknowns, and the degree of confidence engendered by the 17 dB number was an individual matter.

The Phase II vehicle was deployed at Morgantown in greater numbers than before and experienced no uplink interference from the propulsion system either on the old or new portions of the guideway.

In assessment, the decision to use the propulsion unit without retest was found to be correct.

4.2.7 Power Collector Developmental Testing

Laboratory testing of the mutual inductance from power "circuit" (collector plus rail system) to uplink antenna confirmed that the proposed routing, given the wheel spindle location of the collector, was optimum. However, the coupling appeared to be 10 percent (1 dB) higher than before (mid-body mount).

Next, four tests at STTF attempted to determine the resulting uplink noise margin, and this was finally achieved. The program was now better informed, but for two reasons it was not actually further ahead.

1. Accurate correlation of present uplink noise level at the STTF with the 1974-75 level proved impossible due to instrumentation differences and vehicle operation correlation problems (the noise is highly variable).

2. No margin data from 1974-75 for the differential uplink antenna had been taken.

The result was that it was impossible to predict accurately the amount of erosion of the observed margin (17 dB) in actual fleet operations at Morgantown.

Consequently, in July 1978 an attempt was made to link the two situations. Phase IB operating noise was measured by placing current probes around selected power rail feeders (in common mode). The same measurement had been made at the STTF. The result was a noise current at 10 kHz of 1.5 amperes rms in 1 kHz bandwidth. At STTF the corresponding current was 200 ma, almost 20 dB less. This news came so late that no action could be taken. In operation actual levels at the antenna proved to be no greater than before. The cause of the "false alarm" is thought to have been an overly conservative assumption on the ratio of measured feeder current to rail net current at the sites measured. There were also instrumentation differences between the STTF measurements and the Morgantown measurements.

4.2.8 Installation and Checkout Testing

The original Phase II plan was to do an EMC test on each of the two completely new stations. Later, similar tests were scheduled for the two altered stations. (Two stations were unchanged.) In Phase IB little was done at the station level. These remarks address station internal compatibility; the system level test of both Phase IB and Phase II included station EMC measurements on inductive communications between station and vehicle.

The central idea of the tests was to check grounding; grounding is the main EMI difference between a system of racks at the SIL and the same set of racks at Morgantown. At Engineering station some special tests followed up on open questions raised by the SIL test of the Engineering racks.

These tests were not very productive except, perhaps, for Towers, one of the new stations. At Towers the 60-Hz potential difference between station ground and local earth was 12 volts versus a 5-volt arbitrary limit; this occurs during vehicle dispatch. This was, however, acceptable. The interesting aspect was that this station, the largest of the added stations, also was unique in experiencing TV camera noise (Topic 4.1.3) and fare gate logic upsets (Topic 4.2.9). Something about Towers was noisy. However, the 12 volts did not appear to justify deeper investigation. The lack of "productivity" of the grounding tests was a result of the rather heavy ground plane installed in the MPM stations. There is very little difference of potential between points within an MPM station.

A near duplication occurred between the EMC grounding tests and bonding checks in the "power-up" I&CO test. One checks voltage drop under actual operation while the other checks resistance. A combination of both techniques according to situation is best.

Most station I&CO tests, including EMC, were conducted after connection of the station to the guideway loops. There was no "guideway simulator" to enable earlier checkout. The decision to omit the simulator option is clear cut because the interface has too much multiplicity to simulate at reasonable cost.

4.2.9 Fare Gate Test

The vendor tested the fare gate by performing a chattering relay test specifically devised to anticipate installation problems. It passed this test.

Sporadic "computer time-out" problems began to occur after deployment, mainly at Towers. This problem was a reflection of logic upset in the fare gate. An open logic gate input was found and corrected and occurrences dropped to near-negligible. But they continued at a rate of about once a month.

Eventually, a fare gate upset was detected in the electronics maintenance laboratory. A digital designer then found that bypass capacitors normally required for such circuitry were missing. These were added and no more upsets occurred.

Just why the EMI qualification test failed to disclose the deficiency is not known, but the infrequency of the occurrences suggests that the chattering relay was not applied for a long enough period of time.

4.2.10 STTF EMC Testing

Phase IB EMC testing at the STTF was at first restricted to certain measurements that could not be made at lower level and needed resolution well before system deployment at Morgantown. However, when the test came, it was a complete system compatibility test on a finished vehicle.

This test proved to be a learning experience regarding the uplink noise situation. The test came at a time shortly after initial trials of the Phase IB vehicle at STTF had begun to reveal control problems at the berths but before discovery of uplink jamming at Morgantown. Lacking the focus which later uplink tests would have, this general test accomplished much useful design verification but did not succeed in predicting the uplink noise problem.

Basic to test philosophy is the fact that no test can completely mimic actual use. The efficiency with which a test can predict later performance depends greatly on analysis. In this case an updated uplink noise analysis might have guided this test into measurements which would have cut a month or so from the time later spent on problem resolution.

Analysis aside, it must be asked why safetone uplink jamming did not occur at the STTF, yet did occur at Morgantown. First, in clarification, "uplink jamming" occurred at Morgantown with both safetone and stoptone. STTF testing did reveal problems with the stoptone. The probable causes for late safetone problem discovery are:

1. lower rail impedance at Morgantown,

2. electrification geometry differences (STTF: two berths; Morgantown: 40 berths),

3. multiple vehicle additive effect,

4. early power rail problems at Morgantown.

In conclusion, if it is accepted that simply driving a vehicle on a test track will leave some kinds of problems undiscovered, then it becomes important to do good risk analyses. This assumption provides the justification for special tests.

Phase II EMC testing at the STTF was at first aimed solely at the effect of the power collector change on uplink noise. However, by the time the final design verification test was performed, some other measurements had been added. Still, the test was not as complete as the Phase IB test (because the vehicle had, after all, changed very little electrically).

The Phase II STTF test on uplink noise fared little better than did the Phase IB test. Focus was not lacking, but the old difficulties of predicting Morgantown events from STTF data still had not been overcome. Progress was made eventually. A summary of uplink noise test techniques gleaned from Phase IB and Phase II appears below. (See also Section 5.0 for details.)

<u>Uplink Noise Test Techniques</u>

<u>Basic Signal Recording</u> - Spectrum analyzer (select MPM system bandwidth) in fixed-tune mode driving an oscillograph.

A tape recorder can precede the spectrum analyzer.

Noise Probes - Clamp-on current probes on individual conductors and around whole 3-phase bundle (e.g., rail feeder). May be either on vehicle or at wayside.

Antenna Probe - Battery-powered differential buffer.

Margin Techniques

- o Route noise cable close to antenna
- o Introduce gain ahead of receiver
- o Unbalance a differential antenna
- o Reduce signal by shielding antenna
- o Perform stalled rotor tests at selected sites.

4.2.11 System EMC Test

The Phase II test, a close copy of the Phase IB test, included:

Inductive Communication

Uplink noise margin (added gain at receiver)
Downlink noise margin (reduced downlink signal)
Station downlink signal/noise ratio.

Vehicle Internal

Vehicle DC bus noise margin
Tachometer noise margin.

Station Internal

AC bus transients.

These measurements were made for a test fleet of six vehicles. Unmodified portions of the guideway were tested in the same way for margin, but diagnostic measurements were omitted (e.g., the vehicle tape recorder).

The basic method in use was demonstration of uplink margin by inserting gain ahead of the uplink receiver (valid for MPM uplink receivers).

This had been developed during Phase IB and is considered necessary and sufficient for MPM type receivers. Attempts to compute the margin from measurements of noise and measurements of threshold have shown that approach to be unfeasible.

Looking back, the only advisable change would have been to measure a greater number of downlink loops for signal to noise ratio. These measurements were very informative.

5.0 UNIQUE CONCERNS

This section discusses EMC problems that are unique to MPM or unique to transit systems. Some mention of these problems was made earlier, but detailed explanations appear in this section.

5.1 Uplink Impulse Noise

5.1.1 Early Events

The potential problem of motor control SCR pulses interfering with uplink communications was studied in September 1971 and was reported to be no problem. But in the fall of 1974 this interference was found to be a serious problem. Origins of the early optimism are traced in the following review.

The 1971 analysis covered the entire uplink band, but for clarity the following recollection considers only 10.2 kHz, one of the two uplink channels that came to be jammed. First the 1971 analysis and then actual 1974 data follow.

SCR interference at 10.2 kHz to uplink reception was predicted by calculating the magnetic field coupling from the power rails to the uplink antenna location. Geometry was taken to be worst case. The power rails were assumed to be carrying SCR noise current at the maximum level allowed by MIL-STD-461 Notice 3, Test CE-03 (20 ma rms in 1000 Hz BW). The resulting field was 7.1×10^{-10} Tesla rms in 1000 Hz BW.

SCR pulses create an impulsive broadband noise (i.e., having a definite repetition rate), the amplitude of which is ordinarily expressed as a voltage, current or field spectral density such as volts per Hertz. However, the SCR pulse repetition rate (360/sec) is not far different from the VCCS bandwidth (766 Hz), and, therefore, density is not a valid measure. A true measure of impulse noise in this case is the reading of a spectrum analyzer having the same bandwidth as the VCCS.

The standard measurement bandwidth has, therefore, come to be 1000 Hz, the closest to 766 Hz on available spectrum analysers. The "rms" appearing with voltage quotations means that the value quoted is 0.707 of peak voltage. This standardization to 1000-Hz bandwidth for SCR noise was not at first adopted. For example, the VCCS specification describes antenna impulse noise in terms of voltage per 200-Hz bandwidth.

Bendix had apparently not yet released the antenna design but did state a noise field limit which the antenna-VCCS combination could tolerate; this was 1.4×10^{-8} Tesla rms, a sine wave limit. Assuming that the VCCS bandwidth would not exceed 1000 Hz the analysis then concluded that there would be no interference by a factor of 1.4×10^{-8} X 7.1×10^{-10} which is twenty.

The above prediction notwithstanding, the Phase IB VCCS sometimes lost uplink reception due to propulsion noise. Either the Bendix limit was too high for Phase IB, or else the prediction was low.

The Bendix limit proved to have been valid for Phase IB even though it was set in 1971. If the limit is multiplied by the antenna area, number of turns, and frequency, it is found that the Phase IB VCCS would receive from the limit field a noise voltage of 0.35 mv rms at 10.2 kHz; this is about a factor of ten below VCCS noise threshold. Therefore, the threshold criterion against which the 1971 noise prediction was judged was conservatively low.

The prediction of noise field at the antenna proves to have been low. Not only did the controller itself exceed the MIL-STD-461 CE01 limit, but also the coupling mode from that current to the antenna was underestimated. The controller generates up to 700, not 20, ma rms in 1000-Hz bandwidth. In Phase IB the coupling from this current to the field at the antenna was actually about twice the 1971 estimate, and the error in the estimate was the assumption that noise currents in the power rail were balanced (net current zero). Actually, the currents become up to 50 percent unbalanced whenever the vehicle closes a loop in the electrification network. In sum, the actual noise was about a factor 70 higher than predicted.

5.1.2 Phase IB Events

The VCCS specification incorporated uplink impulse noise as an environmental condition. The level was too low by about a factor 4, but no impulse tolerance test was performed anyway.

Whether or not the lack of a developmental laboratory test at this juncture was the result of the 1971 optimistic prediction is not known. The result, at any rate, was that uplink jamming by propulsion noise was first discovered in the field.

A series of STTF tests culminated in development of a differential antenna which provided about 20 dB rejection of the power rail noise field. Two tests at Morgantown, meanwhile, confirmed the dominant mechanism of uplink jamming to be enhanced net current in the power rail during switching and dispatch, a consequence of simultaneous left and right power collector contact.

Concurrent with the above solution to power rail noise field, a filter choke was developed for a ground loop that also was causing a noise field at the uplink antenna.

The differential antenna, the ground loop choke, a reroute of part of the ground loop, and a VCCS change to inhibit response to transitory stoptones all combined to correct the problem of impulse noise in the uplnk.

Besides jamming the safetone, uplink noise also interfered with stoptone. One stoptone problem was a lurching dispatch; upon deliberate removal of stoptone the vehicle would accelerate. The resulting impulse noise in the power rail and in the ground loop was sensed by the uplink antenna and registered as stoptone present. This caused the VCCS to signal for propulsion off. The noise would then subside and the cycle would repeat. The fix for this was to discriminate inside the VCCS against transitory stoptone by waiting before issuing stop commands. In another problem a parked vehicle would dispatch due to apparent loss of stoptone during track power turn-on. The stoptone fix sequence was:

- o Reroute ground loop - partial fix
- o Increase stoptone level - total fix with bad side effects
- o Develop differential antenna
- o Restore stoptone to its original level.

5.1.3 Phase II Events

The prediction prior to implementation of the EMC Control Plan was that relocation of the power collector from mid-vehicle to front axle would increase uplink noise, and that no other changes were significant. The noise did not in fact increase significantly, and there is evidence that an actual improvement in uplink noise resulted from the change from retractable to fixed power collectors and from an uplink transmitter change. First, a brief log of events is presented.

- o A laboratory test showed that the mutual inductance from the forward-located collector net current circuit to the uplink antenna was about 10 percent greater than that from the old mid-vehicle collector circuit (circuit = collector + power rail).

- o STTF tests showed that the noise picked up by the uplink antenna exceeded the allowable cw spurious level.

- o Diagnostic tests at the STTF showed that most of the coupling came from the power rail, not from the collector bundle.

- o Uplink loops were found to carry propulsion noise in the common mode.

- o Speedtone modulation sidebands were found to constitute a source of noise at the safetone frequency of level comparable to that of propulsion noise.

- o A margin test at the STTF showed 17 dB of margin against safetone jamming by noise.

- Rail current noise at Morgantown was measured during the final days of Phase IB operation, and the extrapolated results predicted that interference would occur.

- Qualitative analysis of all design changes since Phase IB showed at worst a degradation of uplink noise margin for Phase II from 6 dB down to 4.5 dB.

- The installed system successfully passed a 6 dB margin test.

5.1.4 VCCS Receiver Characteristics

During all this concern the VCCS receiver response to impulse noise came to be understood. The following is typical of all modulated tone receivers in the VCCS (safe, speed and switch). Assume impulsive interference, that is, pulses occurring at a regular rate. The signal is a square wave 100 percent modulated carrier. The essential features of the response to the interference are listed below.

1. Proper signal strength is irrelevant.

2. Pulses above a certain amplitude threshold cause disruption of the off-cycle of the square wave.

3. If the number of pulses per off-cycle exceeds a certain threshold, then modulation loss is sensed and the channel is jammed (about 0.1 second later).

A description of how this response comes about is given below. Knowledge of this characteristic influences test strategy in that noise amplitude measurements become less important than direct margin measurements. One direct cause is that propulsion noise is not regular enough to permit accurate counting of pulses exceeding the amplitude threshold.

The VCCS modulated tone receiver characteristics are relevant to transit system planning because of their lesson that signal-to-noise ratio is not necessarily the final criterion for link performance. Here are the details. The buffered input signal is passed through a pre-filter of about 15 percent (of carrier frequency) bandwidth before driving the phase lock loop, a circuit entirely contained in one tiny black pellet ("PLL" in Figure 5-1).

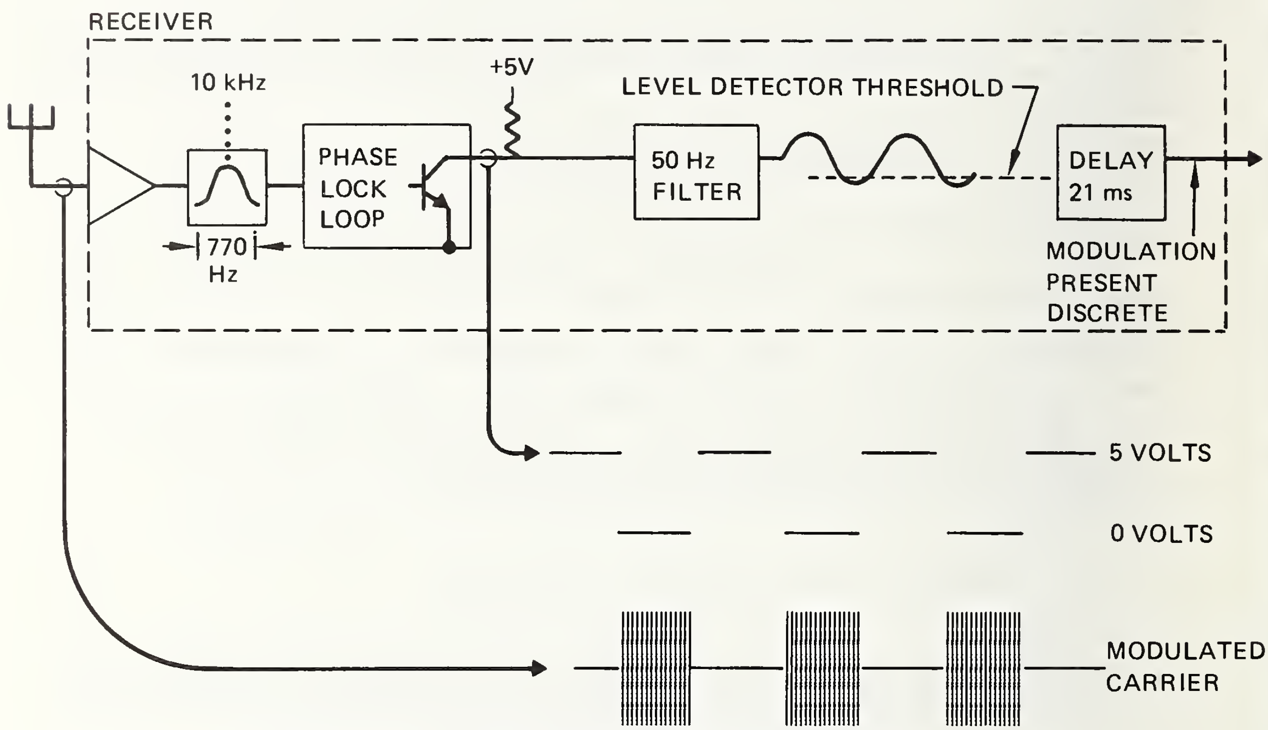

FIGURE 5-1. PHASE-LOCK-LOOP TONE RECEIVER

The PLL oscillator tunes itself up and down until a sine wave signal is put in; this causes the error signal to be nulled, thus fixing the oscillator frequency and switching on the output transistor; that is, when the PLL "locks-on" the output logic goes "low." Given square wave 100 percent carrier modulation the PLL output is a square wave. The presence of this square wave, the object of the whole receiver, is sensed by the ensuing filter, level detector, and anti-dropout delay. Impulse response is determined in a murky way by the PLL and is modified in a readily understood manner by the square wave sensor. Consider propulsion impulse noise, such as the 2-second envelope of Figure 5-2.

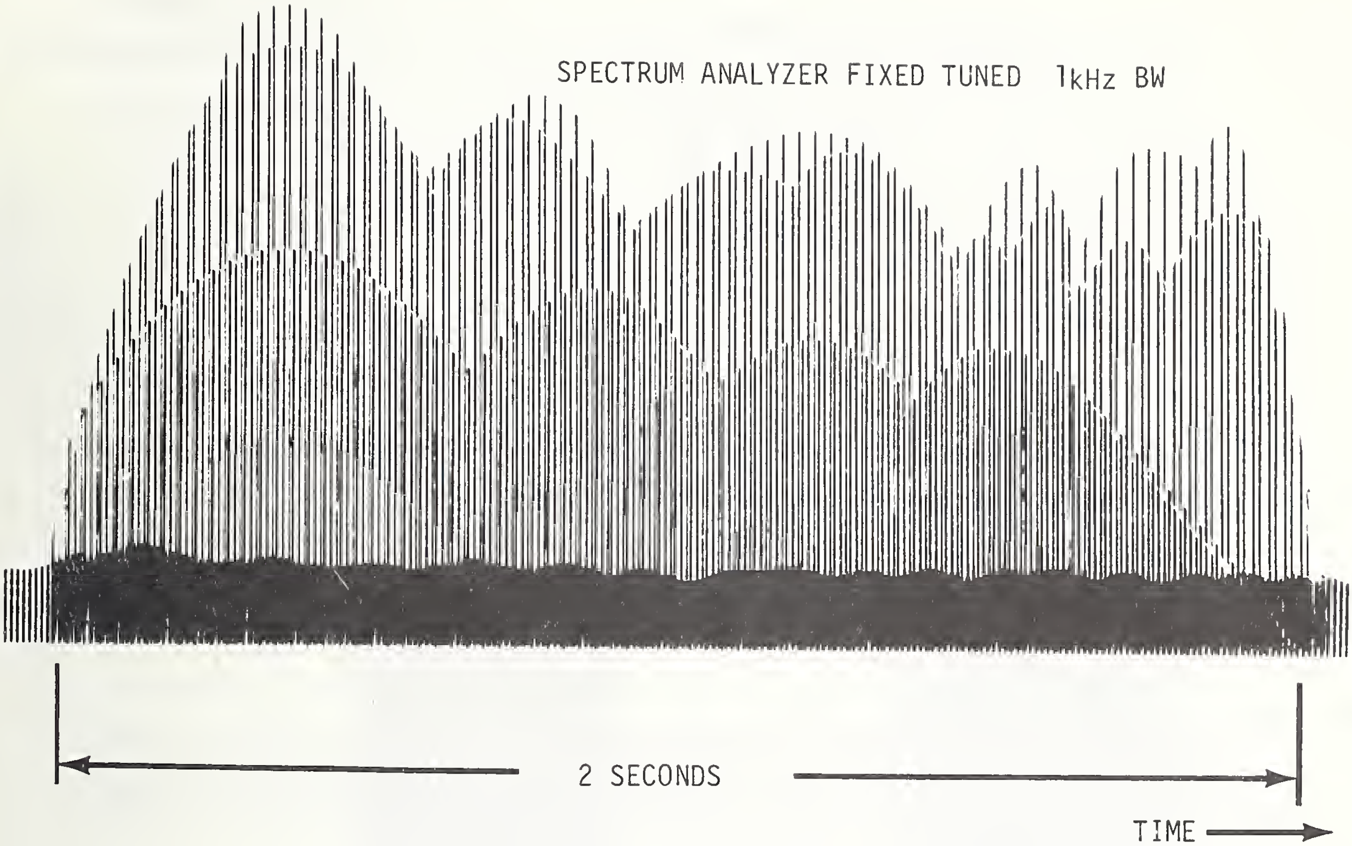

FIGURE 5-2. PROPULSION NOISE AT RECEIVER INPUT

Each of the six SCRs generates an individual pulse envelope at 60 pps resulting in a PRF of 360, 240, 120 or even 60 depending on observation altitude. Superimposed on a square wave modulated carrier, these pulses fill in during the carrier-off periods (Figure 5-3 as detected and displayed by the spectrum analyzer). In response to the degraded signal the PLL will erroneously put out a "locked-on" low logic signal every time a big enough pulse occurs during a carrier-off period. The PLL input voltage threshold for this impulse response is just about the same as that for sine wave response, at least such is the case for the brand of PLL used here. The effect of these defections from a perfect square wave is cumulative; the more the square wave is notched out, the weaker the amplitude of the "ring" in the filter becomes. In particular, a few pulses can block the square wave detector if preceded by a persistent amount of just-tolerable noise. In consequence:

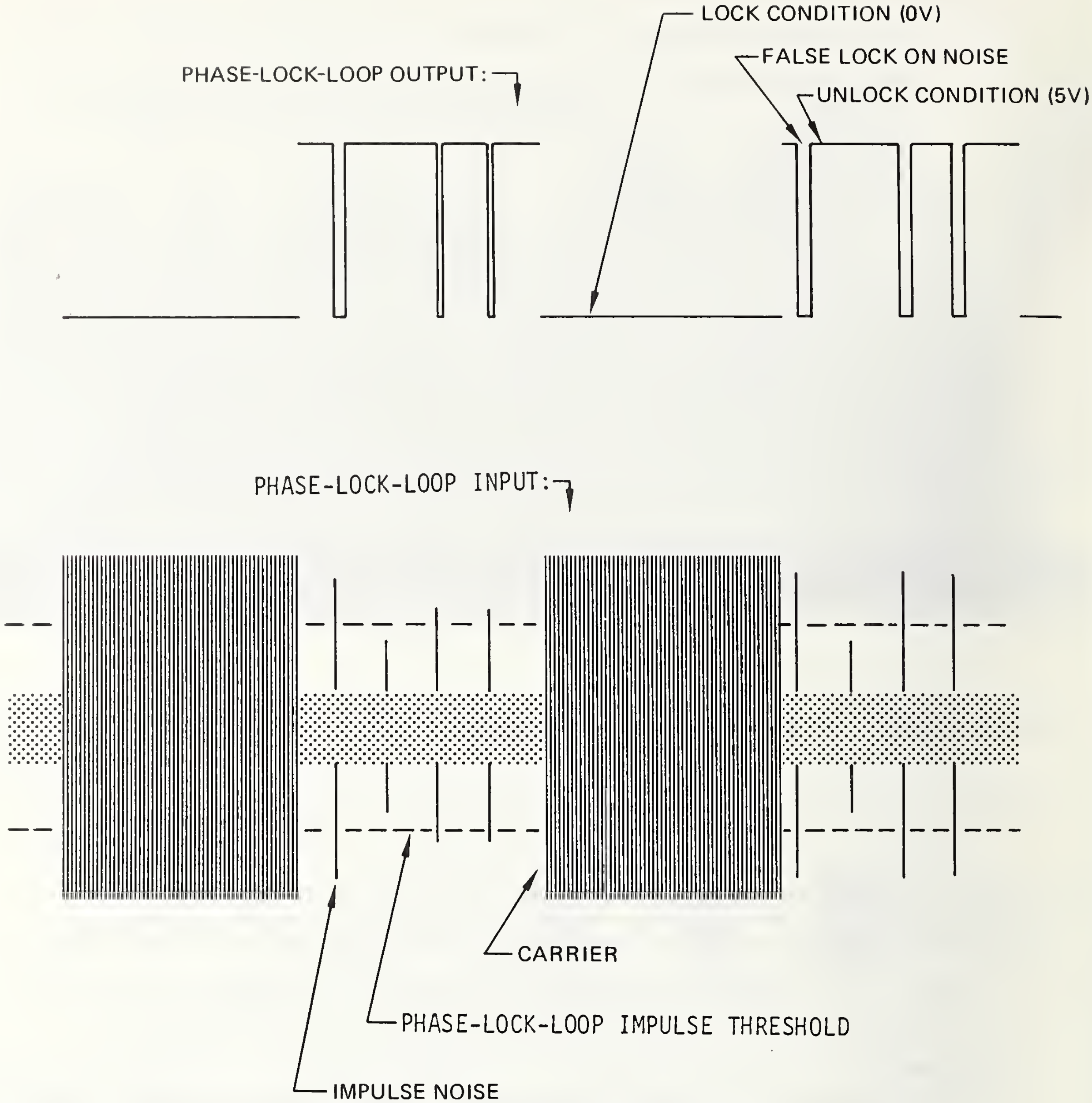

FIGURE 5-3. SQUARE WAVE FILL-IN

1. Increased signal does not compensate for noise.

2. There are two thresholds, an amplitude threshold and a number-of-pulses threshold.

3. Precise determination of margin against impulse jamming by measuring impulse variables (amplitude and PRF) is next to impossible.

5.2 Uplink Antenna Induction Field

Design of the communication uplink to the vehicle rests in part upon the kind and amount of noise produced at the receiver input by the environment. This data was not well known when the uplink scheme was conceived nor even when the hardware was being designed for Phase IB. The following is, therefore, hindsight.

Pickup Sources

Beyond the position of the antenna are located first the immediate sources of field (i.e., conductors) and next the equipment generating the noise currents flowing in those conductors. Electric fields are blocked by the antenna Faraday shield.

The magnetic noise field at the vehicle uplink antenna comes from the uplink loops, the power rails, vehicle power cabling, and, perhaps, a myriad of paths in the steel portions of the guideway. The latter do not seem to be significant. Vehicle power cabling is potentially a source but can be routed to avoid this. The crux of the situation is, therefore, the field of the rails and of the uplink loops.

Experience with the rails proved that their net current rather than their normal mode current was the main field generator. This net flow is caused either by the vehicle's forming a closed path or by two earth connections forming a closed path (Figure 5-4).

Both conditions are present together in most cases. The differential antenna rejects much of the field of the power rails.

The uplink loops have a common mode field of propulsion noise and a normal mode field due to normal mode currents. The first is of minor significance because the differential antenna rejects common flow in the loops (although not completely, because of off-tracking). The normal mode field is sensed by the differential antenna in designed fashion.

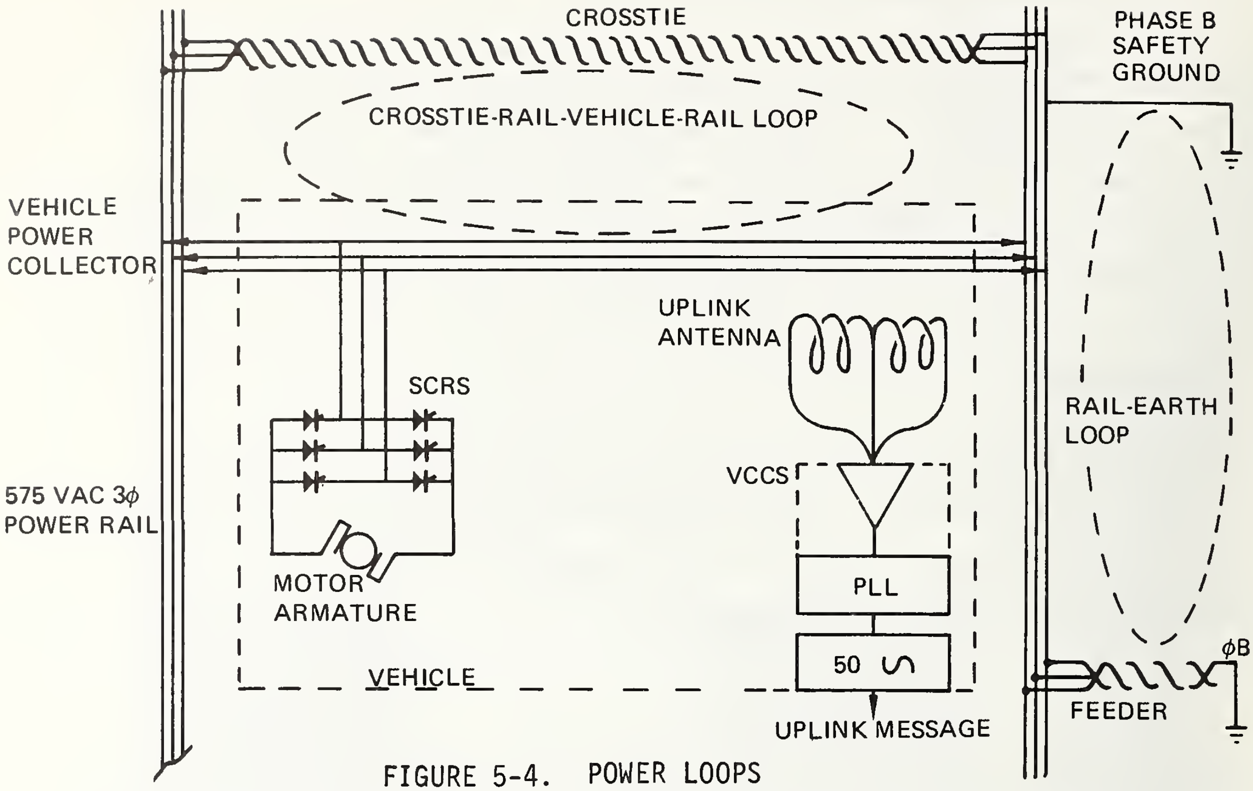

FIGURE 5-4. POWER LOOPS

Noise sources driving the rail and loop currents are listed below on the right:

Induction Source	Signal Source
Rail Net Current	1. Vehicle armature controller
	2. Nearby vehicle armature controller
	3. Vehicle power collector brush bouncing
	4. Nearby vehicle brush bouncing
Loop Normal Current	Uplink signal sidebands and harmonic sidebands.

The MPM propulsion system filters remove such minor noises as the commutator ripple of the DC motor. The noise of importance is that from the six controlled rectifiers (SCRs). When torque demand reaches a certain amount, then the SCR array starts to conduct full-time with the result that momentary shortings of the powerline occur. High amplitude current pulses then are drawn from the power rails (Figure 5-5).

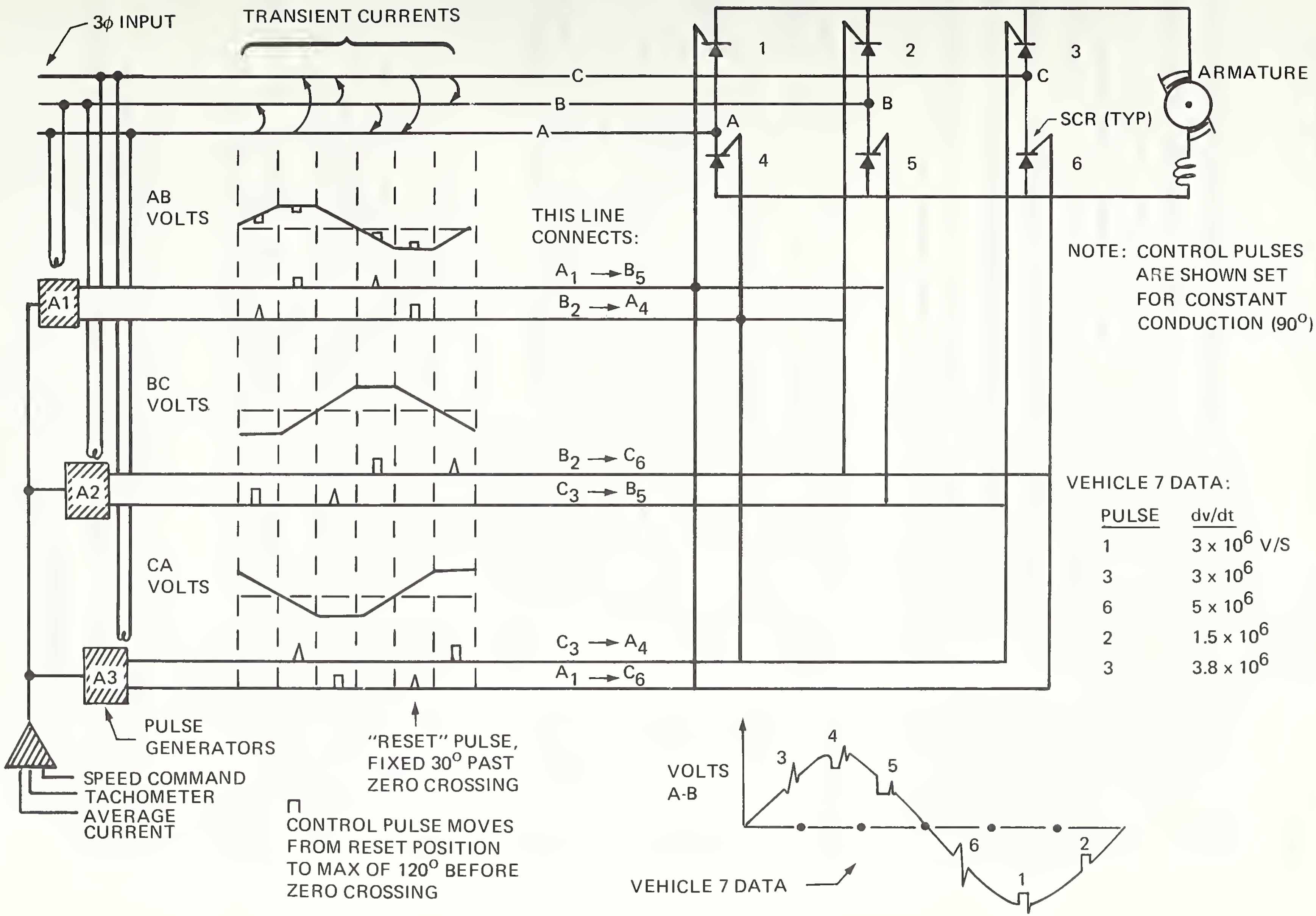

FIGURE 5-5 SCR PULSE FORMATION

At 10 kHz the noise current sensed with 1-kHz bandwidth reaches one ampere during dispatch.

The effect of the above SCR noise is increased by double rail contact during bias switching. This SCR noise is accompanied by power collector brush bounce pulses resulting from bias switching. Oscillograms show that current pulses from helter-skelter break and make of the Phase IB power collectors sometimes are larger than the SCR pulses. Although few in number their effect upon uplink communications is additive. (See VCCS Receiver topic). The fixed Phase II collector generates fewer pulses or lesser amplitude. Nearby vehicles also contribute their SCR and collector noises to the uplink antenna field via the common power rail.

Uplink sidebands are a noise source of equal or greater magnitude than the vehicle SCR noise. Square wave modulation by means of on/off switching creates widespread impulse noise sidebands as a function of switch details. For example, at 10.2 kHz (safetone uplink) the 17.2 kHz speed-tone sideband noise is several times the amplitude of propulsion SCR noise (bandwidth 1 kHz). However, the effect upon the VCCS receiver is about the same as the SCR noise because the PRF of the speedtone sidebands is 100/second whereas that of the SCR is as much as 360/second. The significance of sideband noise eluded early investigators because it is easily mistaken for SCR noise.

Uplink sideband impulse noise is a problem not only at frequencies that approximate the fundamental of the offending uplink, but also at frequencies that approximate its harmonics. Although the uplink frequencies were carefully chosen to minimize harmonic interference, the noise sidebands compromise this protection. For example, the fourth harmonic of the lowest speed tone gets within sideband range of the switchtone receiver.

The chronic problem of uplink sideband noise was alleviated but not eliminated in Phase II by improving the design of the modulating switch in the uplink transmitters.

5.3 Uplink Noise Model

Final acceptance of uplink noise is based upon margin. But the design for that acceptance can only be guided by a goal, however approximate, for noise magnitude. As was noted, only the VCCS can precisely determine the troublesomeness of an interfering signal. An approximate measure has been developed. For 50-Hz square wave modulated tone uplinks the "effective" impulse noise is approximated by the sum of pulses occurring within one "off" period (10 ms). This quantity, call it "I", for Vehicle K in the presence of others is expressed below as the sum of the various contributions previously discussed. A bandwidth of 1 kHz is noted because the expression was developed for the safetone receiver, carrier frequency 10.2 kHz. The variable, X, is position on guideway.

$$I_k(x) = \omega\, A_k(x)\, (rM_r + cM_c + lM_l(x)) + F(x) + \omega\, B_k(x)M_c(x),$$

in which the symbols are as follows:

$I_k(x)$ = pulse total in 10 ms for forward or aft antenna, 1 kHz bandwidth, 10.2 kHz mv rmsat VCCS input.

$A_k(x)$ = Phase A current at 10.2 kHz, 1 kHz bw, ma rms.

$r(x)$ = Fraction of $A_h(x)$ appearing as net righthand rail current, a function of the rail network and rail heat.

$c(x)$ = Fraction of A appearing as net collector current, a different function of the rail network and rail heat.

$l(x)$ = Fraction of A appearing as net CCS loop current, (Normal mode loop current is zero).

Mr = Mutual inductance from righthand rail net current to antenna output, henries; A constant.

$M_c(x)$ = Mutual inductance from net collector current to antenna output, henries; depends on rail network and so upon position.

$M_1(x)$ = Mutual inductance from loop net current to antenna output; depends on off-tracking and so upon position.

$F(x)$ = Speedtone sideband pulse level on FSK loop measured at antenna output; mvrms, a function of loop identity.

$B_k(x)$ = Collector net brush bounce current, total pulse ma in 10 ms.

ω = 2 10,200.

The threshold of the VCCS for the quantity I is about 10 mv rms.

A look at magnitudes is afforded by some data from Vehicle 7 in a right curve at the STTF just past the station:

RH Rail net current, rA (rail heat off)	= 160 ma rms
Collector net current, cA	= 0
Loop net current, 1A	= 30 ma
Inductance to RH rail	= 100 nH
Inductance to collector (forward rail cross tie)	= 40 nH
Inductance to loop (by symmetry)	= 0
Speedtone noise F(x)	= 1.6 mv rms
shoe bounce current	= 0.

The model then gives (rail heat off):

$$I \text{ (curve)} = 2\pi\ 10200\ (0.16 \times 100 \times 10^{-9}) + 0.0016 = 2.6 \text{ mv in 10 ms.}$$

Compare this with Vehicle 7 measured antenna noise of 2.1 mv in 10 ms. The margins below are computed for a receiver of sensitivity 1.8 based on a previously measured effective impulse threshold of 13 mv for a receiver of sensitivity 1.1:

$$\frac{13\ (1.8/1.1)}{2.6} = 8.2\ (18\ \text{dB})\ (\text{model})$$

$$\frac{13\ (1.8/1.1)}{2.1} = 10.1\ (20\ \text{dB})\ (\text{measured}).$$

Compare these margins with the vehicle 7 direct margin measurement of 18 dB with heat off, 20 dB with heat on. Speedtone noise is clearly a big term in total noise.

5.4 Design Change Effect on Uplink Noise Margin

Just before the system EMC test, the Phase II uplink noise margin at 10.2 kHz was predicted by dead reckoning from the Phase IB uplink noise margin of 6 dB. Design changes, new elements, and their anticipated effects as of that date are listed below.

<u>Vehicle</u>

1. Collector move forward should increase the noise by ten percent, 1 dB.

2. Collector extended permanently should eliminate collector bounce pulses (prominent in Phase IB) but will also increase the duration of collector net current. If there are speed transitions in double rail, then this duration change will degrade margin.

3. Collector contact to carbon/stainless from copper/copper should do nothing to collector noise.

4. Antenna cable rerouting should have no effect.

5. Hydraulic accumulator change could warp field by ± 1 dB.

6. Propulsion tubular filter deletion has been measured to have no effect.

7. Closed loop braking may decrease the brake-motor conflict and so decrease noise during emergency stops only - no effect.

8. Deletion of safety shoe lead 10.2 KHz filter (no fourth rail) would increase station noise greatly but for item 9.

Guideway

9. Powering both sides of car at berth compensates for 10.2 kHz filter removal.

10. Rail change to in-line array from triangle array should do little.

11. Phase B change from middle rail to bottom rail should slightly reduce collector net current (in double rail) but have no effect on rail net current due to double earth connections.

12. Substation number two addition should increase noise near Engineering hill by 3/2, or 3 dB.

13. Bonding of steering and bumper rails may increase noise over much of the guideway depending on how well bonded these rails used to be; more of Phase B current will return in the newly good rails. However, where bad loops already existed the bonding will improve the noise Sum; expect improvements.

Station

14. Improved speedtone transmitters will practically eliminate speedtone noise at 10.2 kHz.

General

15. Added guideway electrification is a network whose excitation at 10.2 kHz has not yet been studied.

16. Added cars should have no effect because headway remains the same.

With the exception of the following changes, those listed in items 1 through 16 will not in their aggregate produce a significant effect on noise margin on the guideway:

6	(Phase IB)
-3.5	(Added substation)
-1	(Collector move)
+3	(Estimate of speedtone noise absence effect based on one speedtone pulse per two motor pulses, 30 percent)
4.5 dB.	

5.5 Uplink FSK Leakage

The VCCS FSK receiver is a superheterodyne FM receiver with envelope (non-coherent) detector. It is mainly vulnerable to c.w. interference because any steady tone above threshold will be acquired by the receiver and will prevent acquisition of desired messages. Spurious c.w. at FSK carrier frequencies leaks out of the Phase IB uplink transmitter and causes a chronic problem of this kind. The approach has been to mimic the leakage during VCCS maintenance checkout and, thus, screen out vulnerable VCCS FSK receivers. Phase II FSK uplink transmitters were redesigned and do not leak detectable amounts of c.w.

Such leakage forces the vehicle receiver threshold upward which, in turn, can cause uplink loss due to insufficient signal at weak spots on the inductive communication system. Typically, the coupling becomes weak at merges and demerges where the FSK loop must branch. Uplink drive level cannot be increased at will to fill these weak spots. Prevention of c.w. leakage is therefore important.

Prevention begins with an interface agreement document between vehicle and wayside which sets forth allowable leakage.

5.6 Downlink Noise

Downlink noise in the "switch verify" channel potentially affects system availability; if a "verify" is not received from a vehicle that is passing through a switch location, then that vehicle is stopped by the CAS. Downlink noise in the FSK channel potentially blocks fault reporting and so delays vehicle maintenance.

"Failure to verify" has occurred at some Phase IB guideway locations but has been only indirectly caused by noise. While the evidence is incomplete, it suggests that insufficient signal is the predominant cause of message failure. The threshold of the switch verify receiver of the station electronics has been chosen rather high to avoid false message reception due to noise, itself as unwelcome as message failure. The result is that at sites where either the vehicle off-tracks, or vehicle-to-loop coupling is poor (e.g., at merges), the received downlink strength tends to be insufficient to exceed receiver threshold. Corrective measures are cumbersome. Noise has, therefore, been an indirect problem by virtue of its threat if not by its presence.

Switch verify loop noise prevention measures are known to work, and excessive noise exists only when good practice is ignored. The measures are scrupulous isolation for multiple grounds and a loop transposition at mid-length (30 feet into a 60-foot loop).

FSK downlink noise and signal considerations are similar to those for switch verify.

Downlink noise is interesting because the enormous number of loops, each feeding a dedicated receiver, is a great deterrent to thorough investigation.

5.7 Vehicle Internal Interference

All vehicle internal interferences have been spikes upsetting a binary or latching circuit. Ordinary corrective measures have been effective once a problem was identified.

It is often difficult to identify "one-shot" problem sources. The best illustration is the wire between VCCS and radio. This wire has been there from the beginning but only recently was found to conduct ambient transients to VCCS signal common where they caused logic upset. During Phase II design review the circuit's potential for trouble was discussed briefly. Since there had been no Phase IB difficulties, nothing was done until false fault-status messages occurred regularly in the newly deployed Phase II fleet. Even then, discovery might have been yet further delayed had not a rash of bad wire lug crimps resulted in loss of solenoid diode suppression. This forced the problem into the open.

A minor maintenance problem occurred when hand-held radio transmitters affected a photoelectric tachometer encoder. This maintenance environment should have been figured into the EMC requirements.

A very sneaky trouble path was built into the VCCS in Phase II by the change to a power supply which had a higher output impedance <u>when turned off</u>. The ingredients of trouble were:

1. the power supply change;
2. an interface circuit with voltage present at some but not all times when the VCCS was off;
3. an internal VCCS bus voltage detector setting that responded to the interface (sneak) voltage.

The consequence was that the bus voltage detector failed to do its job which was to initialize the VCCS. Added to the sneaky nature of the cause was the subtle nature of the effect. The circuit that was affected by the imperfect reset was a calibration circuit. Ordinary design assurance descriptions can miss sneak circuits because key questions are not asked. A group at Boeing - Houston has systemized a set of questions and path finding techniques which reliably ferret out latent problems such as the one described here. This group had performed an analysis on the Phase IB system but was not called back for the redesign. The problem just discussed was found experimentally in the maintenance electronics laboratory.

5.8 Lightning Vulnerability

MPM station electronics is apparently vulnerable to lightning through its external cable and loop runs. However, no lightning damage has yet occurred. Some confidence that this was to be the case was obtained by analysis of the Phase IB design.

Induced voltage at the station electronics loop interface was calculated for a direct strike to guideway structure but not to the guideway loops themselves. These lie below the higher steel portions and are presumed, therefore, to be protected. The (common mode) induced voltage proved to be a function of loop length.

Next, the damage threshold of each kind of electronics (two kinds of receivers, two kinds of transmitters) was derived from vendor and in-house data using equivalent circuits.

Combination of the voltage vs. length function with the damage thresholds produced a set of "damage threshold lengths" which then were used as a kind of lightning yardstick to assess the vulnerability of several hundred loops. The actual process allowed for the difference between raised and on-grade guideway. The results were that a direct hit would probably destroy, in terms of statistical averages, the following numbers of circuit cards:

- 4.6 Safetone drivers
- 4.2 FSK drives
- 5.5 FSK receivers
- 1.4 Switch verify receivers.

These are moderate losses for a direct hit. It was decided that the loss from most strikes was, therefore, very small and, hence, acceptable. This judgement has been borne out by experience as no lightning damage to circuitry has yet occurred.

The vehicle antennas were also analyzed for vulnerability with the result that the downlink transmitter was considered to be vulnerable to a strike on nearby guideway structure. The probability of a vehicle being near a strike is less than the probability of a strike; consequently, this risk was accepted. No lightning damage to downlink transmitters has, in fact, occurred.

5.9 Tachometer Problems

The MPM tachometer-odometer sending unit is an optical device attached to the driveshaft. An occulting disk sends light pulses to a photo-transistor.

This transistor proved to be sensitive to UHF as emitted by maintenance walki-talkie radios (but not to the vehicle radio whose antenna is on the roof). Cabling changes managed to reduce the pickup below the threshold of most transistors; this left a small scale selection problem.

The sender was receiving 10 volts/m or more from the walkie-talkie compared to a control plan figure of 1 volt/m for vehicle c.w. environment.

6.0 POTENTIAL SYSTEM IMPROVEMENTS

The following suggestions are expressed in MPM terms but are perhaps translatable to other programs.

6.1 Risk Prediction

Risk prediction studies were useful and should be done. However, uncertainty in prediction should be faced and allowed to modulate the degree of authority with which the predictions are regarded (i.e., mathmatics notwithstanding, knowledge that the armature pulses were going to be a problem). More emphasis should be placed on early tests.

6.2 EMI Requirements

Correlation between requirements and results was negligble for Station Electronics. Only the powerline environment (100 volts here) should be validated and retained. But the other requirements, the ones on susceptibility to fields, can be deleted.

Vehicle electronics requirements were useful as far as they went. A test for susceptibility to cable pickup transients should be added.

Central Electronics, like Station Electronics, needs a valid description of powerline transients and does not need field susceptibility limits. All the Phase IB EMI problems were caused by long line effects that are difficult to simulate in a bench test. Development of practical EMI simulation of long lines like those at Morgantown is needed.

6.3 Design

The VCCS ground loop between local VCCS ground (0.1 μFd common-to-case) and dc ground should be eliminated by cutting the ground tie. Common mode rejection requirements should be placed on all interface circuits. In all systems having a computer, the dilemma of grounding everything either at the computer or at the power distribution arises. The correct solution is to ground each to local structure and to place isolation or balance in all interconnecting circuits; by this means ground loops are avoided.

VCCS interface 28 volt wiring should not be bundled with lower voltage interface wiring in the run between case connector and circuit card.

In the propulsion unit certain shared return impedances could have been eliminated had additional connector pins been available. The problem arises in the quick-change design which introduces multi-pin connectors between major modules. These connectors are full.

The VCCS phase-lock-loops may not necessarily be vulnerable to impulse noise just because they are designed to lock-on quickly to a sine wave. Whether or not a basic improvement in their noise immunity is possible is not presently known.

6.4 Design Assurance

Complete schematics of the system must be drawn before approving drawings.

Complete single-line schematics of guideway electrification should be done early enough to support fault calculations and safety analyses.

Sneak circuit analysis should be done on selected areas of the system, and changes should be re-analyzed.

6.5 Testing

A prototype armature controller and a prototype VCCS receiver should have been coupled inductively to determine the threshold of the VCCS for this particular pulse sequence form.

Cable transient pickup tests patterned after MIL-STD-461 RS02 should be applied to vehicle electronics equipment..

Transient susceptibility testing in general should be developed to increase availability of proper gear and validation of limits.

APPENDIX A - REPORT OF NEW TECHNOLOGY

The report collects the MPM electromagnetic compatibility (EMC) experience of ten years, assesses that experience, and complements the assessment with a review of basic EMC principles.

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