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POTENTIAL MEANS OF COST REDUCTION  
IN GRADE CROSSING MOTORIST-WARNING  
CONTROL EQUIPMENT  
Volume II: Comparison of Solid State and  
Relay Devices and Techniques

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16. Abstract  Consideration is given to the properties of solid-state circuits, miniature relays and large gravity-operated relays when applied to control systems for grade crossings equipped with train-activated motorist warnings. Factors discussed include original cost and service-life cost, vulnerability to environment, reliability and fail-safety, power requirements, maintainability, complexity of tasks to be performed and economic scale.					
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11. These findings have important implications for the field and should be shared with the wider community.

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## PREFACE

The work described in this report was part of an overall program at the Transportation Systems Center to provide a technical basis for the improvement of railroad-highway grade crossing safety. The program is sponsored by the Federal Railroad Administration, Office of Research and Development.

This volume, the second of a two-volume report, includes an analysis of reliability aspects of grade crossing warning system hardware and an assessment of the relevance of solid-state devices to this application. An executive summary, overview of the entire subject area, general examination of the problem and consideration of special types of relays will be found in Volume I.

# METRIC CONVERSION FACTORS

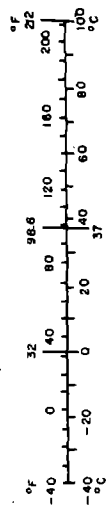
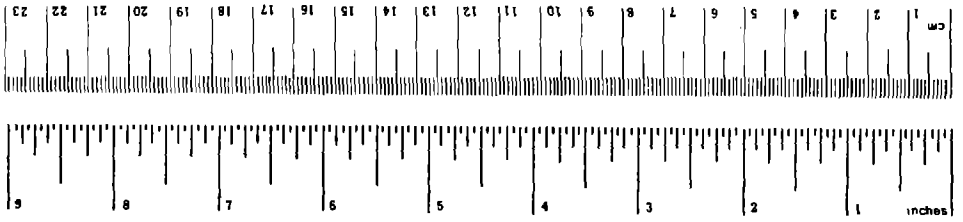
Approximate Conversions to Metric Measures		Approximate Conversions from Metric Measures	
Symbol	When You Know	Multiply by	To Find
<b>LENGTH</b>			
in	inches	2.5	centimeters
ft	feet	30	centimeters
yd	yards	0.9	meters
mi	miles	1.6	kilometers
<b>AREA</b>			
in <sup>2</sup>	square inches	6.5	square centimeters
ft <sup>2</sup>	square feet	0.09	square meters
yd <sup>2</sup>	square yards	0.8	square meters
mi <sup>2</sup>	square miles	2.6	square kilometers
	acres	0.4	hectares
<b>MASS (weight)</b>			
oz	ounces	28	grams
lb	pounds	0.45	kilograms
	short tons (2000 lb)	0.9	tonnes
<b>VOLUME</b>			
tsp	teaspoons	5	milliliters
Tbsp	tablespoons	15	milliliters
fl oz	fluid ounces	30	milliliters
c	cups	0.24	liters
pt	pints	0.47	liters
qt	quarts	0.95	liters
gal	gallons	3.8	liters
ft <sup>3</sup>	cubic feet	0.03	cubic meters
yd <sup>3</sup>	cubic yards	0.76	cubic meters
<b>TEMPERATURE (exact)</b>			
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature

Approximate Conversions from Metric Measures	
Symbol	When You Know
<b>LENGTH</b>	
mm	millimeters
cm	centimeters
m	meters
km	kilometers
<b>AREA</b>	
cm <sup>2</sup>	square centimeters
m <sup>2</sup>	square meters
km <sup>2</sup>	square kilometers
ha	hectares (10,000 m <sup>2</sup> )
<b>MASS (weight)</b>	
g	grams
kg	kilograms
t	tonnes (1000 kg)
<b>VOLUME</b>	
ml	milliliters
l	liters
l	liters
m <sup>3</sup>	cubic meters
m <sup>3</sup>	cubic meters
<b>TEMPERATURE (exact)</b>	
°C	Celsius temperature
°F	Fahrenheit temperature

Approximate Conversions to Metric Measures	
Symbol	When You Know
<b>LENGTH</b>	
cm	centimeters
m	meters
km	kilometers
<b>AREA</b>	
cm <sup>2</sup>	square centimeters
m <sup>2</sup>	square meters
km <sup>2</sup>	square kilometers
ha	hectares
<b>MASS (weight)</b>	
g	grams
kg	kilograms
t	tonnes
<b>VOLUME</b>	
ml	milliliters
ml	milliliters
l	liters
l	liters
m <sup>3</sup>	cubic meters
m <sup>3</sup>	cubic meters
<b>TEMPERATURE (exact)</b>	
°C	Celsius temperature
°F	Fahrenheit temperature



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## 1. INTRODUCTION

A large gravity of a type called the "vital" relay is the standard logical element currently used in the circuits that control operation of gates and flashing lights at railroad-highway grade crossings in the United States. A typical grade crossing employs up to a dozen relays interconnected to perform the sequential operations required to operate flashing lights and gates. The source signals fed into the relay logic system are dc track voltages, or ac track signals and coded signals from which dc logic signals are derived.

It is natural to ask, Why in this age of integrated microcircuitry, when electronic switches or logical elements can be packaged at a density of hundreds to the square inch and at a cost of a few cents per element, is there continued use of logical elements in grade crossing applications that have a size of many cubic inches and a cost of approximately \$100 per element? The purpose of this report is to put this question in perspective by considering the many aspects related to the design and operation of grade crossing logic and control systems. Characteristics of solid-state components will be compared to large gravity relays. In addition, the properties of miniature spring-return relays of a type used in European railroad signalling applications will be discussed.

The considerations that are discussed in this report include: original cost and service-life cost; environmental factors including temperature, electric surges, and noise; reliability and fail-safety; power requirements; maintainability; complexity of tasks performed; liability aspects; and the economic scale of the overall problem. Consideration of these characteristics will be seen to demonstrate why it is that large gravity "vital" relays will no doubt play the major role in grade crossing logic systems, at least in the immediate future, while solid-state circuits will be used increasingly in special applications.

## 2. CHARACTERISTICS OF INDIVIDUAL DEVICES

### 2.1 VITAL RELAYS<sup>1/</sup>

Vital relays have a number of specific electrical configurations each adapted to a specific circuit function. In all configurations, an electric current is passed through the windings of an armature coil to create the magnetic force required to lift the armature physically and switch the relay contacts in one direction. Upon interruption of the electric current, the force of gravity returns the armature to its rest position. A typical vital relay for use in a 10-volt dc circuit has a coil resistance of approximately 100 ohms; thus, the relay will draw 0.1 amperes and dissipate 1 watt when energized. Track relays are vital relays designed to operate at very low voltage and power levels for sensing track voltage. They typically have coil resistances of 2 to 4 ohms, have a pick-up current of approximately 0.1 amperes and dissipate approximately 0.02 watts when energized.

The design of vital relays has been refined to a high state over the years. Present standard design features include nonmagnetic armature stops and back-up armature stops to prevent lock-up in the energized position due to remanent magnetization of the magnetic circuit, nonmetallic front contacts to prevent the welding of front contacts by surge currents, placement of terminals and leads to maximize the ability to withstand voltage

surges, and enclosure in tight transparent cases that offer cleanliness and ease of visual inspection in the field. Mechanical and electrical integrity is enhanced by sheer physical size--approximately 5 inches in height, width, and depth, and several pounds in weight. Allowable temperature range of operation is extreme and is determined by the permissible range of operating temperature of the nonmetallic insulating materials used in construction. Relays are designed to withstand surges of 3,000 volts coil-to-ground, and the inductance of coil windings serves to minimize surge current through the windings due to surges of short duration. The physical size and inherent inertia of the moving parts of the relay serve the function of providing low-pass filtering to minimize the effects of noise on proper electrical operation. In the grade crossing application, the large size of these relays does not exact a particular penalty, since they are used in a fixed ground-based application; and a dozen of them can be housed in an enclosure that is not out of scale with other pieces of hardware required in a grade crossing motorist warning system, such as flashing light masts and battery cases. The excellent ability to withstand surges inherent in these relays makes possible fairly reliable operation in the field with the addition of a minimum of other surge protection compared to what is necessary with solid-state components. Further, even at a cost of approximately \$100 per relay, the total

cost of logical elements at a grade crossing is still a very small part of the overall cost of an actively protected crossing.

## 2.2 MINIATURE RELAYS<sup>17/</sup>

Particular types of miniature spring-return relays are routinely used in European signalling applications. In comparison to vital relays, they cost approximately one-third as much, occupy approximately one-twentieth the volume, consume several times the electrical power (approximately 5 watts), and have somewhat less ability to withstand surges--a typical figure being 2,000 volts. Service lifetime is less than that of large gravity relays, and their smaller physical size leads to less ruggedness, a shorter maintenance interval, and greater proneness to failure. The large power requirement--greater than that of gravity relays--is due to the fact that a smaller size means a magnetic circuit of smaller cross section. Yet, proportionally more magnetic force is required to reliably overcome spring tension to lift the armature than is needed in a gravity relay.

## 2.3 SOLID-STATE COMPONENTS

While it is true that solid-state components can be thought of as providing the same logical circuit function as electromechanical relays, all of their other characteristics put them in a completely separate class. A single logic gate

performs the same logical function as a relay or a number of relays. As mounted in circuits, integrated circuit logic gates have a packing density on the order of 10 gates per cubic inch--provided the gates are packaged in 14-pin flat packs which in turn are mounted on circuit boards. Packing densities attainable with medium-scale integration (MSI) and large-scale integration (LSI) are many times larger. Price per gate for industrial-quality components is on the order of \$1.00. Power requirements range from on the order of 0.5 watts per gate, to essentially zero watts per gate in the case of CMOS logic operated at low switching rates. Surge ratings are on the order of volts rather than thousands of volts. Allowable maximum operating temperature is generally restricted to +85°C, although devices capable of operating up to temperatures of 125°C are available at premium price. Sensitivity to surge damage and temperature cycling effects leads to failure rates and estimated lifetimes in service that are almost entirely a function of measures taken to control the electrical and thermal environment. However, a solid-state component operating in a surge-free environment at a temperature in the range of 30°C has virtually unlimited lifetime--certainly greater than any electromechanical component.

Microprocessors--essentially one- or two-chip digital computers--serve as an extreme example of the state of the art of solid-state circuitry. Thousands of logical elements are

packaged per cubic inch, and relatively complex arithmetic or logical operations can be performed involving on the order of 10 input signals and 10 output signals. Cycle time is a fraction of a millisecond, and provided the purchase volume is large enough, price can be as low as \$10.00 per complete microprocessor. However, to realize this price, very large volume is necessary. As was indicated by one semiconductor manufacturer, \$50,000 will buy you either one complete unit programmed for a specific application, or 5,000 units. Nearly all the price is in the tooling. After that, manufacturing the chips is practically free.

### 3. LOGICAL FUNCTIONS PERFORMED BY CONTROL SYSTEMS AT ACTIVELY PROTECTED GRADE CROSSINGS

#### 3.1 A TYPICAL GRADE CROSSING WITH FLASHING LIGHTS

Figure 1 shows a circuit diagram for a typical grade crossing with flashing light protection but no gates. This example serves to demonstrate the types of logical operations that are performed by the control system in determining when the lights should start and stop flashing.

The signals that are sensed to indicate the approach or presence of a train are track voltage signals that originate either from dc batteries, which are impressed between the tracks through series current-limiting resistors, or that originate from signal generators generating coded ac signals. In either case, when any part of a train occupies a section of track, the solid axles and wheels of the train short out the corresponding electrical signal, and the absence of signal then signifies the presence of some part of a train in that section of track.

In the diagram shown in Figure 1, a single track is shown and this is divided into three sections--East, Island, and West. Corresponding track voltage signals are fed to individual relay coils. The East and West track signals are fed to separate windings of a so-called "interlocking relay." This relay has two armatures and an arrangement of cams that interlock the motion of the armatures in such a way that both



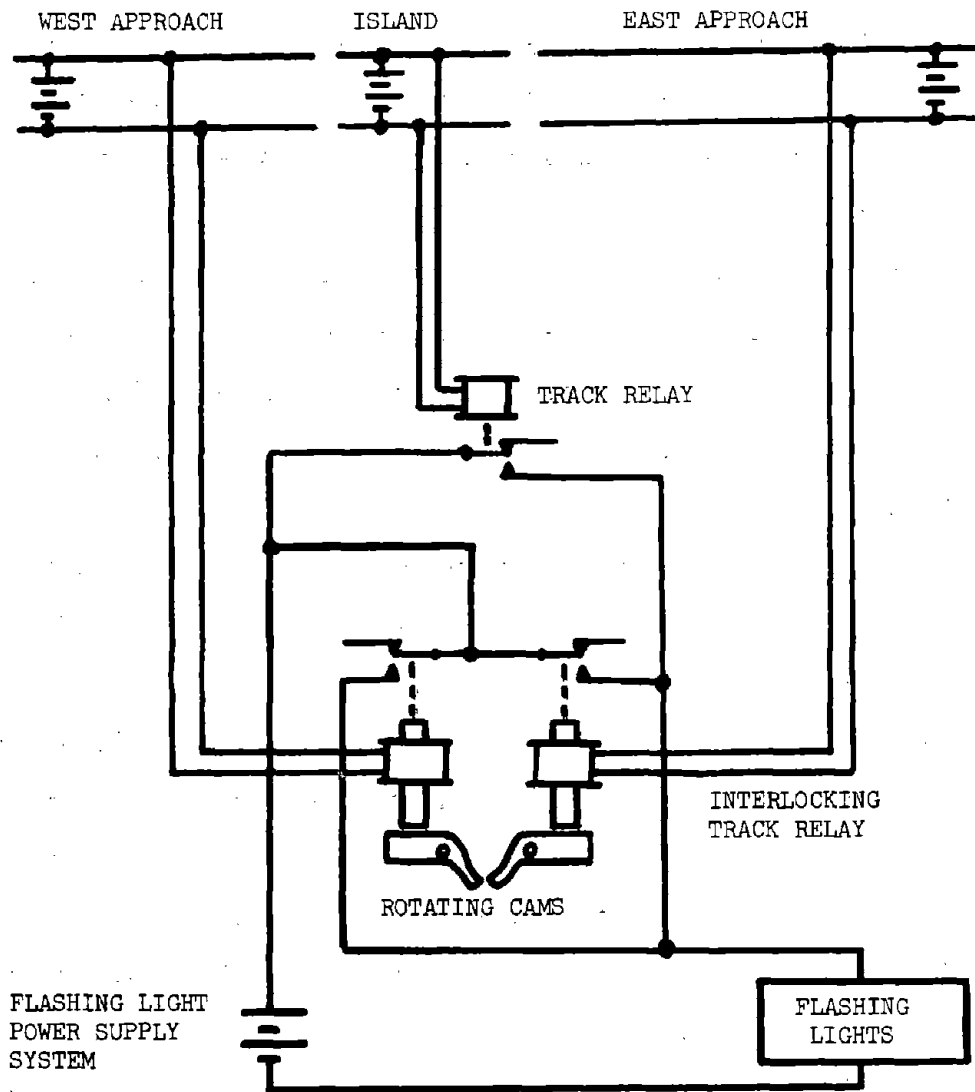


FIGURE 1. SIMPLIFIED ELECTRICAL DIAGRAM SHOWING OPERATING CHARACTERISTICS OF A GRADE CROSSING FLASHING LIGHT CONTROL SYSTEM. (System shown uses three track circuits and an interlocking relay. Not shown are current-limiting resistors always used in series with track batteries, electrical details of flashing light power supply system, and light flasher circuitry.)

cannot fully drop simultaneously. Thus, the positions of the two armatures depend on the sequence in which track signals disappear and reappear. The desired mode of operation can be realized, in which the lights start flashing when an approaching train coming either from East or West enters the corresponding section of track; and the lights stop flashing as soon as the trailing end of the train leaves the Island section of track. From the circuit diagram, one sees that the lights will flash whenever either the East, West, or Island relay back contacts are closed.

The interlocking relay operates as follows: Assume that no train is initially present and so both East and West coils are energized and both armatures are up; a train arriving from the West will cause the West coil to be de-energized, and the West armature will drop, closing the West back contacts, and starting the lights flashing. The West armature will bear against the West cam, causing it to rotate into a position that will interfere with the rotation of the East cam. When the train passes through the Island circuit and into the East section of track, the East coil will de-energize, causing the East armature to drop, also. The East armature will not drop all the way, however, since it will bear against the East cam, which is prevented from rotating. Therefore, the front contacts of the East part of the relay will open, but the East armature will not move far enough to close the back contacts of the East part of

the relay. Furthermore, when the train has completely left the West section of track and the West armature has picked up, the West cam will still be stuck in position by the force of the East cam bearing against it; in turn preventing the East cam from rotating far enough to permit the East armature to drop far enough to close the East back contacts. Then, although the train still occupies the East section of track as it recedes from the crossing, neither West, East, nor Island back contacts are closed and the lights will stop flashing. When the train finally leaves the East section of track, the East armature will pick up, returning the entire system to its original state.

### 3.2 BOOLEAN ALGEBRAIC STATEMENTS FOR GRADE CROSSING OPERATION

A particularly useful mathematical technique for analyzing the operation of circuits performing logical functions is the application of Boolean Algebra<sup>3/</sup>. Boolean Algebra is used in situations in which each parameter in a problem can be defined to exist in a specific state or not exist in that state. For instance, at least ideally, a track voltage is either sufficiently greater than zero to assure that it will cause a track relay armature to pick up, or the voltage is essentially zero. Likewise, a relay armature is either up, or it is dropped. In the case of an interlocking relay, a particular cam is either fully rotated, or it is not fully rotated. The values zero (0) and one (1) are assigned to a variable corresponding to an

event, depending on whether the event is not occurring or is occurring.

In the case of the grade crossing protective system described above, the following Boolean algebraic variables can be defined:

$L = 1$  when lights are flashing,

$E = 1$  when East coil is energized and East armature is up,

$W = 1$  when West coil is energized and West armature is up,

$I = 1$  when Island coil is energized and Island armature is up,

$C_{W,E} = 1$  when West, East cam is not fully rotated,

$B_{W,E,I} = 1$  when West, East, Island back contacts are closed.

Then using the notation generally used in Boolean algebra

$\bar{A} = 1$  when  $A = 0$ , and vice versa,

$AB = C$  implies that  $C = 1$  when  $A = 1$  and  $B = 1$ ,

$A + B = C$  implies that  $C = 1$  when  $A$  or  $B = 1$ ,

the entire logical sequence of operations performed by the control system described in Section 3.1 can be written as

$$L = B_W + B_E + B_I$$

$$B_W = \overline{(W + C_W)} = (\bar{W})(\bar{C}_W)$$

$$B_E = \overline{(E + C_E)} = (\bar{E})(\bar{C}_E)$$

$$B_I = \bar{I}$$

$$\bar{C}_W = \overline{[(C_W + E)W]}C_E$$

$$\bar{C}_E = \overline{[(C_E + W)E]}C_W.$$

Using the logic circuit symbols commonly used for gates performing various functions, as shown in Figure 2, a logic circuit diagram can be drawn that completely characterizes the logical operations performed by the control circuit of Section 3.1. The circuit diagram is shown in Figure 3.

### 3.3 CONCLUSION

A very general mathematical description has been given for the logical operation of the simple grade crossing used as an example. It is obvious that many different types of hardware could conceivably be used to perform the logical operations required to control the flashing lights or other protective devices used at a grade crossing, no matter how complex it may be. As a matter of fact, in spite of the greater initial expense, it is generally considered desirable to use a larger number of separate relays rather than a single interlocking relay to perform the functions just described.

Electromechanical relays are used to perform the NOR, NAND, OR, AND, and Inversion operations by suitably placing contacts of relays in series or in shunt to energize the coils of following relays, and by using either back or front contacts to control the flow of current to following relays. (Back contacts close when an armature drops; front contacts close when an armature is picked up.)

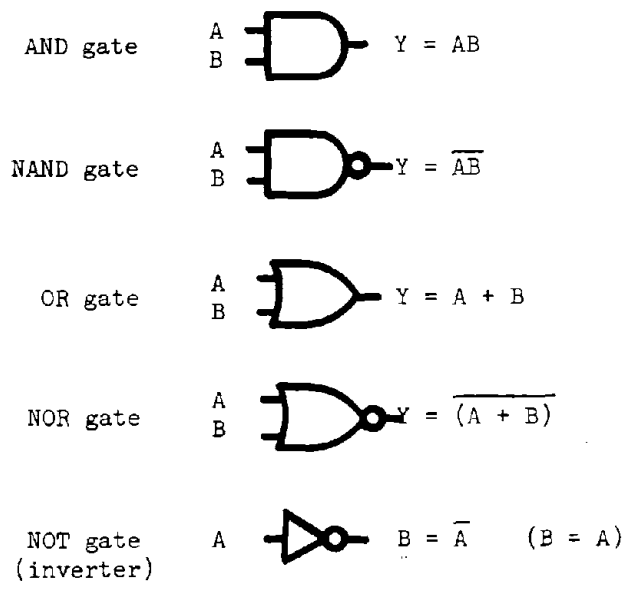


FIGURE 2. LOGIC GATES FOR PERFORMING ELEMENTARY LOGICAL FUNCTIONS

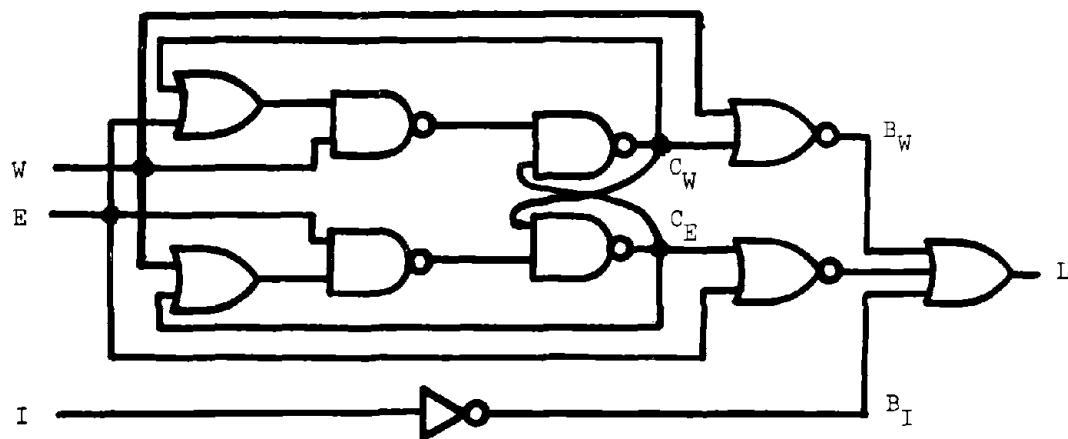


FIGURE 3. THE LOGIC DIAGRAM CORRESPONDING TO THE SINGLE-TRACK GRADE CROSSING CONTROL SYSTEM USING WEST, EAST, AND ISLAND TRACK SECTIONS

Semiconductor logic circuits could be employed in each step, even up to providing the actuating signal for a solid-state flasher relay for flashing lights, or a power transistor switch circuit for controlling a gate motor.\* The primary purpose of this study is to investigate the desirability of pursuing this course of action.

---

\* One major manufacturer of grade crossing protective equipment in the past has marketed such a system. The system consisted of solid-state audio-frequency overlay (AFO) track signal generators and receivers, solid-state logic module, with output signals provided for light flasher and gate control. The system was removed from the market because of lack of buyer interest.



#### 4. TECHNICAL CONSIDERATIONS AFFECTING CHOICE OF COMPONENTS FOR GRADE CROSSING CONTROL SYSTEMS

##### 4.1 COMPLEXITY OF TASKS THAT CAN BE PERFORMED

As is obvious from the analysis in Section 3, the logical operation that must be performed at a typical grade crossing is very simple. Few logical steps need be performed. Given the small number of logical circuit elements typically involved, and the small number of interconnections that must be made in wiring the circuit, no great penalty in installation costs accrues due to the use of large gravity relays. Logic circuit wiring is such a small part of overall installation at the typical grade crossing that essentially nothing would be gained by using the more sophisticated techniques associated with solid-state components.

Situations do arise, however, in which circuit complexity is much greater, and in which there is a far greater degree of logical complexity. An example of this is the situation in which constant motorist warning time must be provided in spite of a wide distribution in train speeds. In the past, it was standard procedure to use "timing blocks" in the track circuitry--additional sections of track, each energized by its own track battery--to measure the speed of approaching trains. Electromechanical clock relays were used to obtain indication of the speed range of approaching trains and to activate gates

and flashing lights at proper times. The more timing blocks and clock relays employed, the finer the gradations of train speed that could be measured. Systems employing timing blocks demanded much greater maintenance, since the clock relays themselves were unreliable and since much more track circuitry had to be maintained. (Systems were designed so that clock relay failure resulted in maximum warning time being given.)

In the case of constant-warning time systems, the greater inherent logical complexity and circuit complexity tips the balance in favor of solid-state logic systems. Logical operations that would require large numbers of separate relays and interconnections to be made in the field can be performed by a small solid-state module that is factory wired and tested. Such a solid-state module must be protected against the electrical and thermal environment, but such protection can be made at a very small fraction of the price that would accrue if electromechanical relays were used for the entire system. In addition, when proper environmental protection is provided, the fact that the solid-state logic system has no moving parts to wear leads to less requirement for maintenance than would be the case if electromechanical relays were used.

In situations where part of a grade crossing system consists of solid-state circuitry for performing complex logical functions, it would probably make sense to maximize the number

of logical functions performed by solid-state logical elements and to minimize the number performed by electromechanical relays. Having already decided that solid-state circuitry is required because of the inherent complexity of the job to be done, and having already paid the price for the required environmental protection for the solid-state equipment, there should be at best a few dollars more expense for solid-state equipment to perform all necessary logical operations within the solid-state portion of a system. Clear savings would then amount to approximately \$100 for every electromechanical relay eliminated. Redundancy techniques within the solid-state circuitry could be employed to achieve desired performance levels of fail-safety and reliability.

In summary, the complexity of logical operation that must be performed at a specific grade crossing is an important consideration in determining whether electromechanical relays or solid-state circuitry should be employed. In the very simple cases, it appears that electromechanical relays are the best choice. In the more complicated cases, such as when constant warning time or motion sensing are required, it appears that all logical operations should be performed within a single solid-state module, and electromechanical relays should be eliminated entirely. It should be noted that such all-solid-state systems have been marketed in the past by major signal suppliers.

## 4.2 FAIL-SAFETY AND RELIABILITY

The issues of fail-safety and reliability of grade crossing protective systems are very important and very emotional issues. The fact that emotions often enter discussions of grade crossing system performance is not surprising, since human lives, corporate fortunes, and professional reputations are so directly at stake.

Grade crossing protective systems are elements of our overall socioeconomic system that are employed to protect human life and property while allowing the efficient operation of trains over tracks with as little disruption of automobile traffic as possible. From the viewpoint of economic analysis, grade crossing protective systems should be designed to minimize the sum of protective system costs plus economic disruption costs plus accident costs, where accident costs include property damage costs and dollar figures appropriately placed on human lives and suffering. Such a global consideration is not within the objectives of this report; however, these ultimate considerations should be at least kept in mind as problems of grade crossing safety are addressed.

The analysis of hazard detection systems rests on application of techniques from the fields of estimation theory, detection theory, and decision theory, all of which in turn are based on application of probability theory. In a more restricted

sense than that described above, it can be assumed that the purpose of a grade crossing protective system is to detect correctly the hazard presented by the approach of a train that will move through the crossing, and to indicate correctly when no hazard is indeed present. Two types of errors in system operation are possible. In detection theory parlance, these are called misses and false alarms. In the case of grade crossings, a miss is an erroneous indication that no train is coming when in fact one is; a false alarm is an erroneous indication that a train is coming when in fact one is not. Both types of errors have costs associated with them. The cost of a miss is obviously very high, and is immediately calculable in terms of human lives and dollars.

The costs of a false alarm are also of non-zero magnitude but these costs are more subtle. In spite of the subtleness associated with costs of false alarms, it is generally recognized that these costs exist. Needless disruption of automobile traffic is an obvious cost. An additional cost, whose payment is deferred until a later time, arises from the conditioning of motorists to disregard gates and flashing lights at grade crossings that they subsequently encounter.

As will be indicated below, in the design of a specific detection system, there is generally a tradeoff between designing for low false alarm rate and designing for low miss rate. One can

generally decrease both error rates simultaneously, if one is willing to increase the overall complexity and cost of the system.

Where one defines

$c_E$  = annual equipment cost

$c_M$  = cost of a miss

$c_F$  = cost of a false alarm

$r_M$  = miss rate

$r_F$  = false alarm rate

$c_{Total}$  = total annual cost

the optimum design of a system such as a grade crossing protective system is the design that minimizes the quantity

$$c_{Total} = c_E + r_M c_M + r_F c_F.$$

In practice, it is impossible to reduce either  $r_M$  or  $r_F$  ideally to zero. However, current railroad signalling practice and current practices associated with the design of grade crossing protective systems call for the use of techniques, given a maximum allowable system complexity, that make every operational choice possible in a direction that lowers the miss rate  $r_M$ , whatever the effect may be on the false alarm rate  $r_F$ . This principle of design is called the Principle of Fail-Safe Design, or the Fail-Safe Principle. No detection system of any type for any application is ever absolutely fail-safe. However, judicious application of the fail-safe principle can lead to miss rates that are dramatically small, as has been done in the case of railroad signalling and grade crossing protective systems.

In designing systems, redundancy techniques are frequently used to decrease error rates, at the expense of increased equipment costs. As an example of the factors involved, consider the case shown in Figure 4a where the occurrence or nonoccurrence of an event E is sensed  $r_S$  times per unit time. A sensor S is used to sense the occurrence of E, with values  $E = 1$  for occurrence, and  $E = 0$  for nonoccurrence. On each sensing, there is a probability  $P_M$  that an actual occurrence will be missed, a probability  $P_F$  that although E does not occur, it will be falsely indicated as occurring, a probability  $(1 - P_M)$  that an occurrence will be accurately sensed, and a probability  $(1 - P_F)$  that a nonoccurrence will be accurately sensed. The miss rate and false alarm rate are then respectively

$$r_M = P_M r_S, \quad r_F = P_F r_S.$$

If the false alarm rate is unacceptably high, one might use the comparative system shown in Figure 4b. In this system, the output Y will only take on the value 1 when sensors  $S_1$  and  $S_2$  both sense that  $E = 1$ . Since a false alarm at Y will now occur only when  $S_1$  and  $S_2$  simultaneously produce false alarms, the probability of a false alarm at Y is

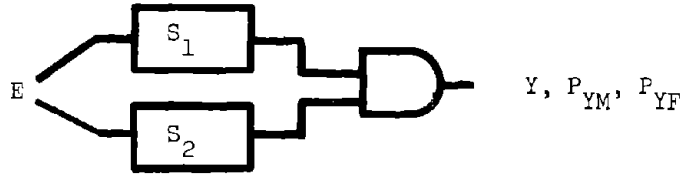
$$P_{YF} = P_F^2 < P_F.$$

On the other hand, the probability that a miss at Y will occur is

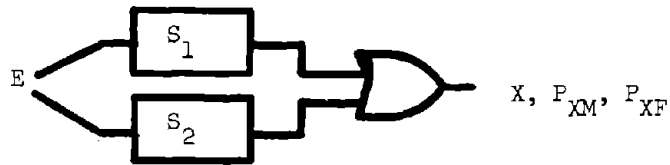
$$\begin{aligned} P_{YM} &= 1 - P(S_1 \text{ and } S_2 \text{ correctly detect}) \\ &= 1 - (1 - P_M)^2 \\ &= 2P_M - P_M^2 > P_M. \end{aligned}$$



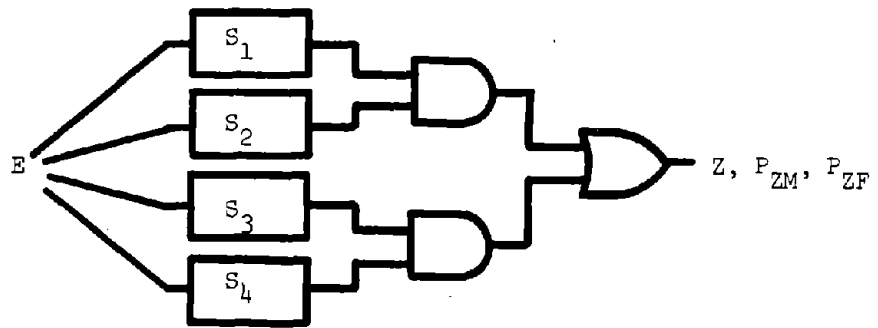
a) Detecting an event.



b) Redundancy to decrease  $P_F$ .



c) Redundancy to decrease  $P_M$ .



d) Redundancy to decrease  $P_M$  and  $P_F$ .

FIGURE 4. REDUNDANCY TECHNIQUES FOR DECREASING ERROR PROBABILITIES ASSOCIATED WITH UNRELIABLE SENSORS USED TO DETECT PRESENCE OR ABSENCE OF EVENT E



Thus in this case, the price that has been paid for decreasing the false alarm rate has been greater system complexity, and greater miss rate.

If one wishes to decrease the miss rate without regard to the false alarm rate, one might use the system pictured in Figure 4c. In this case, the output variable X will take on the value 1 when either  $S_1$  or  $S_2$  indicate that  $E = 1$ . For this case, the output miss and false alarm rates are

$$P_{XF} = 2P_F - P_F^2 > P_F$$

$$P_{XM} = P_M^2 < P_M.$$

If one wishes to decrease both miss rate and false alarm rate simultaneously, one might use the system shown in Figure 4d, with overall output Z, and miss and false alarm rates

$$P_{ZM} = P_{YM}^2 = 4P_M^2 - 4P_M^3 + P_M^4$$

$$P_{ZF} = 2P_F^2 - P_F^4.$$

As an example, if  $P_M = P_F = 0.01$ , then  $P_{ZM} = .0004$ , and  $P_{ZF} = .0002$ .

Given a situation in which one could afford to use four sensors, application of the principle of fail-safe design would call for use of the comparison circuit shown in Figure 5. In this case, the overall system misses detecting an actual occurrence of event E only when all four sensors miss. However, a false alarm

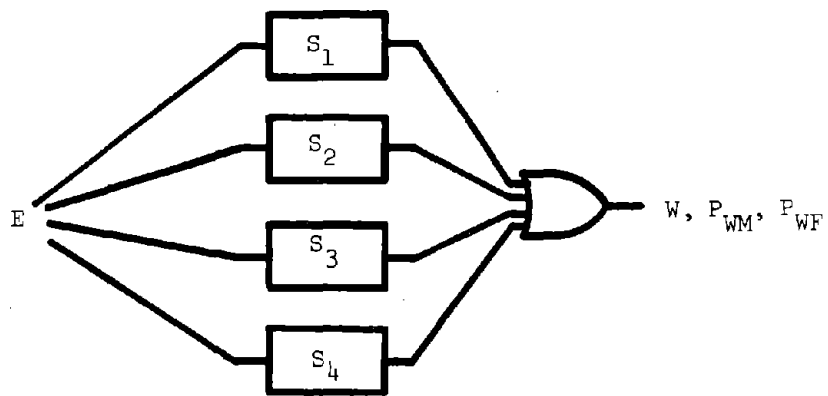


FIGURE 5. THE CIRCUIT YIELDING THE LOWEST OVERALL MISS PROBABILITY POSSIBLE OF ANY CIRCUIT USING FOUR SENSORS

occurs whenever any of the four sensors causes a false alarm.

Thus,

$$P_{WM} = P_M^4 = 10^{-8} \ll P_M$$

$$P_{WF} = 1 - (1 - P_F)^4 = .0398 > P_F.$$

Many other redundancy schemes are possible for improving system performance, such as voting logic. In all redundancy schemes, system complexity increases, and decisions must be made on the basis of relative costs whether to employ the increased complexity to decrease the false alarm rate, the miss rate, or both, or whether the added complexity is worth it at all.

In many systems such as standard railroad grade crossing protective systems, special precautions have been taken in system design to minimize the miss rate. In fact, given the level of complexity customarily employed and the possible combinations of internal interconnections commensurate with that level of complexity, wherever possible, the choice has been in the direction of minimizing the miss rate. The effort to minimize the miss rate, coupled with reliance on individual components that are highly reliable in operation, together assure strict adherence to the fail-safe principle. If one chooses to design a hazard detection system by using whatever design freedom one possesses to decrease the miss rate, at whatever cost to the false alarm rate, then one is designing according to the fail-safe principle. This principle of design is often valid from

an overall cost-effectiveness viewpoint, but, to reiterate, when one is designing a system, one must remember that in the real world, the miss rate cannot be driven exactly to zero, and in making the proper tradeoffs between miss rate and false alarm rate, one must accurately assess the costs of both false alarms and misses.

In standard grade crossing protective systems using vital electromechanical relays of the large gravity type, redundancy techniques are not employed. The design of relays themselves--including absence of return springs and use of non-welding back contacts--coupled with extensive use of the back contacts to close flashing light circuits should practically anything go wrong, serves to provide a very low miss rate in the face of component failure or track circuit failure. Minimization of the false alarm rate is then enhanced by design simplicity which keeps the component count low.

Miniature spring-return relays of a type called safety relays are used in Europe for performing logical control functions at grade crossings. The systems using these relays typically employ redundancy in the form of checking circuits to check the viability of relays. One way of performing this checking is to sense the position of contact pairs that are not being used in the primary circuit. For instance, if a pair of front contacts are closed when the relay armature is de-energized and

the contacts should be open, perhaps the return spring is broken, and the armature is being held in the closed position by remanent magnetization. If a pair of front contacts are opened when they should be closed, perhaps a pair of back contacts have been welded together by an electrical surge, thus preventing the relay from picking up. (Relays are designed so that back and front contacts cannot close simultaneously.) If the checking circuit senses the nonviability of components, the system reverts to a restrictive aspect until it is serviced. In the type of system just described, components are used that do not have the reliability of large gravity relays. Redundancy techniques can be employed to bring the miss rate down to an acceptable level; however, this is done at the expense of false alarm rate, and at the expense of increased maintenance. In this instance, the money saved by not using large gravity relays must be balanced against these other associated costs.\*

Solid-state techniques offer the greatest reward for application of redundancy techniques.<sup>2,6,7,8,9,15/</sup> The physical volume occupied by active elements is such a negligible part of a solid-state system, and interconnection techniques can be so efficient if automation is used, that there is frequently a

\* Limited use has been made of this approach in this country in all-relay interlocking systems. Reliability problems have been encountered; however, these appear to stem more from specific packaging shortcomings rather than from problems of the basic concept. (See Ref. 10.)

very small cost penalty incurred when component counts are doubled or quadrupled. In solid-state systems, redundancy can be used to the extent that failures of individual sensors or internal components do not immediately lead to failure, but simply lead to "degraded performance" in the form of increased probability of ultimate failure. High maintenance levels may be required to repair systems that are degraded, even though they have not failed.

#### 4.3 ENVIRONMENTAL FACTORS

Large gravity relays and miniature spring-return relays can be considered to be essentially immune to the North American climatic environment. Relay systems can perform perfectly at any temperature encountered out-of-doors, or even inside an instrument case being heated by the direct rays of the sun. Under certain limited circumstances humidity presents a problem, such as when the temperature rapidly drops from above freezing to below freezing when humidity is high, causing ice to form temporarily on electrical contacts. To alleviate this problem, heaters are sometimes used to heat relays and prevent this problem.

Semiconductor circuits, however, are greatly affected by temperature and generally must be protected from high temperature extremes. In wide areas of the United States, the summer sun will heat a metal relay enclosure well beyond the acceptable temperature limit for reliable operation. In such circumstances,

if solid-state equipment is to be employed, special means must be taken to limit temperature to an allowable value. Depending on the severity of the situation, shading, forced ventilation, or air-conditioning may be required. The cost of providing and maintaining such thermal protection must be taken into account in calculating overall costs of solid-state systems.

Throughout much of the United States relatively high failure rates of electromechanical relays and other components occur due to lightning-induced electrical surges. There exists here as in other problem areas an economic tradeoff that must be made between the costs of equipment and the costs for protection for that equipment. Semiconductor circuits and devices are inherently many orders of magnitude more sensitive to the effects of electrical voltage or current surges, and it is essential that they be protected in a manner that increases their reliability to a level commensurate to that of electromechanical components. Since surge protection is generally applied to the leads entering a system, and since system complexity and component count generally increases at a greater rate than the number of leads, it appears to be more advantageous to use solid-state circuits and pay the extra for protection in those cases where an inherently complex task is to be performed. However, where a relatively simple task is to be performed, a few electromechanical relays with the minimal protection they usually get will probably cost less in the long run.

## 5. ECONOMIC FACTORS

The economic factors considered below are the questions of who pays for grade crossing hardware--including original hardware costs, maintenance, and replacement; who pays the costs when there is an accident; and, what does electrical equipment of various types cost.

### 5.1 PROCUREMENT AND MAINTENANCE

Currently, the railroads receive substantial money from governmental agencies for the purchase and installation of grade crossing protective systems. The railroads specify what hardware will be purchased and governmental agencies pay for it. Then, after the equipment is in service, the railroads maintain it. (In some locales, governments underwrite part of the maintenance expenses.) This system operates to make it desirable for the railroads to minimize their future maintenance and replacement expenses, independent of whatever costs are involved for initial procurement. It is not certain that this circumstance leads to the lowest overall lifetime costs for grade crossing equipment, or to the lowest yearly costs including amortization and maintenance; nor is it certain that it does not. What does seem to result is a situation in which there is little cost incentive to search for ways of providing required levels of grade crossing protection at lower total yearly costs--equipment purchase, maintenance, and replacement costs included.



What would probably occur if solid-state systems were used to perform the logical functions at grade crossings would be that original electrical equipment costs would decline markedly, but maintenance and replacement costs would rise. Use of miniature electromechanical relays would probably lead to a situation between that of large gravity relays and solid-state systems.

If solid-state equipment were introduced in much larger quantity than is now the case, maintenance costs would rise greatly at least in the short term due to the fact that either new maintenance personnel specially trained to handle solid-state equipment would have to be hired, or current maintenance personnel would have to be retrained extensively. In addition, statistical considerations lead to the requirement of a proportionately larger spare parts inventory for backing up a small number of a specific type of system than for backing up a larger number. The required spare parts inventory required to support the field use of a certain type of system rises less rapidly than the number of systems in use. Thus, unless any new solid-state techniques became very widespread, the relative spare parts costs associated with each solid-state system in use would remain large.

In theory, once modern solid-state techniques became widely used, ease of maintenance made possible by extreme modularization, coupled with general knowledge of maintenance techniques and lower costs of replacement parts compared to vital relays,

would lead to maintenance costs that would be as low as those currently encountered.

## 5.2 COSTS OF LITIGATION

In many circumstances, it currently appears that costs of equipment for grade crossing protective systems are only of secondary importance compared to legal costs arising from litigation following grade crossing accidents. Indeed, a railroad interested in innovating in the area of grade crossing protection may find itself on the horns of a dilemma. If it starts installing equipment of a new type that is not widely used throughout the United States already, and accidents occur at crossings with the new protection, it might be claimed in court that the accidents occurred because of the alleged unreliability or dangerous unfamiliarity of motorists with the nonstandard protective equipment. On the other hand, if accidents occur at crossings that have not yet received the new protection, it might be claimed in court that the older protection was clearly inadequate, as indicated by the fact that even the railroad was now using "better" equipment. Because of these financial pressures on railroads, that result from the fact that they must appear in civil court, there is probably an economic force acting against equipment innovation that might lead to greater overall cost-effectiveness, including lower installation and

operation costs for grade crossing equipment, and lower accident rates as well.

One other conservative factor as far as choice of electromechanical components for grade crossing protective systems is concerned, is the relative ease with which their operation can be understood by potential litigants and juries. In the face of a potential lawsuit to be brought by an allegedly aggrieved individual against a railroad, an exact replica of the grade crossing's electrical control system can be constructed and used to demonstrate in a vivid fashion its fail-safe characteristics. Very frequently the demonstration of the fail-safe design of the grade crossing protective system is sufficient to keep the case out of court.

If a case goes to court, such a demonstration often suffices to convince a jury. In addition, it is relatively straightforward for a signal engineer to take the stand and testify, certain in his heart and in his mind, that the entire grade crossing protective system, including every component in it, could not have failed in an unsafe way and was in safe working order as verified by simple electrical and visual checks.

It perhaps would be far more difficult for a potential litigant, a jury, or even a signal engineer himself to accept fully, on an emotional level, an argument that although a redundant solid-state control system was partly degraded in

reliability, due to a few predictable component malfunctions that had occurred within the statistically determined maintenance interval just passed, a statistical analysis based on the fault tree diagram and predicted component failure rates showed that it was highly unlikely that the grade crossing accident that resulted was the fault of the grade crossing protective system. In spite of the fact that the solid-state system in question could be in actuality even more fail-safe than a corresponding electromechanical system, the people involved might well be unconvinced. The human mind hungers for certitude.

### 5.3 ECONOMIC SCALE

Currently, approximately 50,000 grade crossings in the United States have train-activated motorist warnings, and the number is increasing at a rate of approximately 1,500 per year. As markets for industrial goods go in this mass-production age, this is a relatively small market. Given the longevity of electromechanical components currently in use in large numbers, the replacement market is also small. There is little economic justification, therefore, for individual equipment suppliers or individual railroads to invest large sums for development of revolutionary new components or techniques for grade crossing applications. The potential payoff for any individual equipment supplier or railroad, each concerned with only a fraction of a small market is simply not that great.

A number of factors could change this picture in the future. If a large-scale program on a national level were undertaken for rail electrification, much of the existing signal equipment currently in use on the nation's railroads would have to be altered or replaced in a relatively short time, and the market would greatly expand. The Federal Government might well pay a substantial portion of the resulting costs, thus focusing the economic impact onto one purchaser--the Federal Government. As a result, it might become in the government's interest to underwrite development costs for new types of grade crossing protective equipment based on greater applications of solid-state techniques.

If the Federal Government or local governments or some combination of both were to take over the responsibility for operating and maintaining grade crossings and grade crossing protective systems, this alone would focus the economic impact, since then one party would be responsible for all the life-cycle costs of grade crossing protective equipment including procurement, installation, and maintenance. In addition, the question of liability probably would not be as large a consideration for government as it is for private railroads.

It therefore appears that any move in the direction of centralizing the financial and legal responsibility for grade crossing protection in the hands of the government would increase the economic forces pushing in the direction of technical innovation, including more extensive use of solid-state techniques.

## 6. SUMMARY AND CONCLUSIONS

There are a variety of technical factors that influence the decision as to what type of electrical hardware to use in grade crossing protective systems. These include the complexity of the logical operation that must be performed at a specific grade crossing, questions of reliability and fail-safety, ruggedness of different types of components, and resulting precautions that must be taken against thermal or electrical damage. In addition, there are important economic factors related to assessment of procurement and maintenance costs, costs arising from litigation, and development costs for new types of equipment.

The requirements for increased use of systems providing constant warning time for motorists or motion sensing will lead to greater use of solid-state equipment at grade crossings. In those situations where such solid-state system components must be employed, consideration of all factors involved will probably lead to the conclusion that all-solid-state systems are optimum-- or at least systems in which an absolute maximum of logical functions are performed by solid-state means and an absolute minimum by electromechanical means. For the most complex of logical tasks, microprocessors may become economically viable. In situations where solid-state techniques are used, redundancy techniques will be employed to guarantee acceptable levels of fail-safety and reliability.

In those circumstances where acceptable operating characteristics can be obtained by use of simple electromechanical logic circuits, current economic and technical factors tend to favor the continued use of systems constructed using large gravity relays. However, even here it is conceivable that the economic picture could change sufficiently in the future to bring about greater use of solid-state techniques.

In many respects, the case of miniature relays appears to fall midway between the extremes of large gravity relays on the one hand and solid-state techniques on the other. For a variety of applications, this may be the case. However, whereas use of solid-state techniques essentially solves the problem of moving part failures in large systems, miniature relays are more prone to mechanical failure than the large gravity relays that they replace. Thus, in most instances where a change is made away from the use of large gravity relays, this author predicts that all factors combined will tend to favor a jump directly to solid-state techniques.

## 7. REFERENCES

A variety of technical books, published articles, and unpublished reports were used as reference or background material in the preparation of this report. In addition, valuable information was obtained orally and through correspondence from a number of individuals associated with railroad suppliers, railroads, and the U. S. Department of Transportation. Since much of the information gained orally was done so in an informal manner, often without knowledge on the part of respondents that their statements or views would help shape a report such as this, those people will not be named directly in this list of references. However, the author would like to indicate that a great debt of gratitude is owed to all such persons who so materially assisted in the performance of this work.

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