Model of the Effects of Rail-Highway Grade Crossings on Emergency Access

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The purpose of this research was to develop a simple model describing the impacts of rail-highway grade crossings (RHGCs) on emergency access. Linear cities and two-dimensional cities with square grid roadway networks are considered. For the purposes of the model, maximum response time from the emergency services base stations to the most distant point in the service area was minimized. The model indicates that the introduction of an RHGC into an optimized condition requires each base station to be relocated toward the RHGC, to again achieve optimal conditions. It also reveals that the impacts of a rail line through a city vary greatly with the orientation of the rail line relative to the roadway grid. Suggestions for further model extension are presented.

A rail-highway grade crossing (RHGC) is an at-grade intersection of one or more railroad tracks and a roadway. At such a crossing, railroad vehicles and roadway vehicles must share the right-of-way. RHGCs are unusual in transportation engineering in two respects—first, at an RHGC, two different types of traveled way intersect and must time-share the right-of-way. This is not unique—where highways and waterways intersect at drawbridges, right-of-way is also time-shared. Secondly, at an RHGC, right-of-way is allocated between two competing flows by a continuous favoring of one flow (rail traffic) over the other (highway traffic), without regard to the volume of traffic on the highway. This last aspect is unique to RHGCs.

This continuous favoring of rail traffic results in delays to highway users. Such delays have quantifiable costs, including the time of the delayed motorists, additional vehicle operating costs, and costs of additional air pollution. These costs can be substantial, but are generally not catastrophic.

A special type of delay cost is incurred, however, when an emergency vehicle is delayed at an RHGC. Delays to emergency vehicles can, in the most extreme cases, result in the loss of human lives. In less severe cases, these delays can result in additional property damage (as in the case of fire apparatus being delayed in reaching the scene of a fire). These costs are not obvious, and frequently go completely unnoticed until they are incurred.

A review of the professional literature was conducted; no information related directly to this topic was found. This paper briefly documents a model describing the impacts of RHGCs on emergency access.

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MODEL DEVELOPMENT: LINEAR CITY CONDITIONS

Ideal Conditions, Without RHGCs

Assume the existence of a completely isolated linear city. The city is one block wide, with a single roadway extending through the entire length of the city. All emergency services (fire or medical) must be provided from within the city, because it is completely isolated. Further, assume that the demand for emergency services is distributed uniformly across the city, and that there are no impediments to transportation at a maximum speed of v in the city; in other words, the city is an ideal transportation surface. Emergency services must be provided from a single base station, and maximum response times (travel times to points most distant from the base station) are to be minimized. For the purposes of this model, minimizing the maximum response time was preferable to minimizing the average response time, to maintain consistency with typical fire protection agency policies. In Baltimore County, Md., for example, an effort is made to have first-due units in urbanized areas a maximum distance of 1.5 mi from the most remote points in their service areas.

In a setting such as this, shown in Figure 1, the logical choice for a single base station for emergency services would be C, the geographic center of the city. From such a base station, all points in the city would be reached within T, the maximum tolerable response time. Relocation of the base station to another point, say $C1$, would, of course, shorten some response times, but it would also raise some response

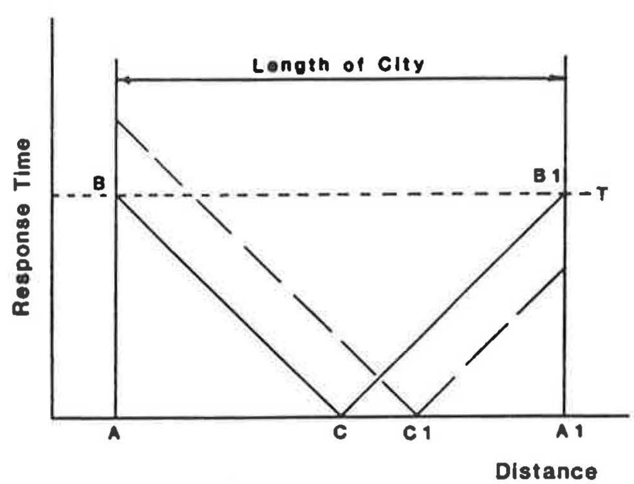

FIGURE 1 Response time versus distance, one base station.

times to intolerable levels. This is also shown in Figure 1 (dashed line); the absolute value of the slope of each line in this figure is v.

Strictly speaking, it may be proven that C is located at the center of the city. Because the absolute values of the slopes of the service time lines (BC and $B1C$) are identical, angle BCA is identical to angle $B1CA1$. In addition, $AB = A1B1$; furthermore, by definition, angle BAC and angle $B1A1C$ are identical, each being a right angle. Because two of the angles in triangle ABC are identical to two of the angles in triangle $A1B1C$, the third angle in triangle ABC (angle ABC) must also be identical to the third angle in triangle $A1B1C$ (angle $A1B1C$). Because the three angles and one side are identical for the two triangles, the other two sides of each triangle must be identical as well. Thus,

$$AC = A1C$$

and

$$AC + A1C = A1A$$

By substitution,

$$2AC = A1A \qquad (1)$$
$$AC = A1A/2$$

Thus, C is the center of the city.

Inclusion of RHGCs

Let us now relax the assumption of the ideal linear city, and assume that a single-track railroad extends across the entire city at any location other than the center of the city. Assume further that each time an emergency vehicle needs to cross this track it is blocked by a train, and is delayed for a time d. The results of this condition are shown in Figure 2, with the base station located at C, the original optimal location, and with the rail line located at F. Figure 2 shows the following:

1. Response times are completely unaffected for locations on the same side of the track as the base station.
2. All locations on the opposite side of the track from the base station will suffer an increase in response time. In fact, some locations beyond F will have response times greater than T (the former maximum).

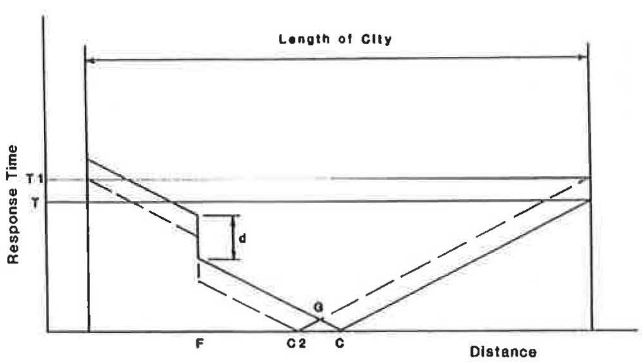

FIGURE 2 Response time versus distance, one base station with RHGC.

In order to optimize this modified system, and meet the objective that maximum service time is to be minimized, T needs to increase at both endpoints of the city. Because there are two endpoints, each needs to accommodate one-half of the delay d caused by the track. Thus, T will increase by $d/2$. In addition, because distance is directly related to travel time by v, the optimal location of the single base station will shift toward the railroad track as follows:

$$s = v(d/2) \qquad (2)$$

where s is the distance of the shift and the other variables are as defined before. The new optimal location will be $C2$, as shown in Figure 2.

The resultant response times are also plotted in Figure 2 (dashed line), and show that the maximum response time increases by $d/2$, to $T1$. In fact, response times increase for most individual points in the city, decreasing only for the areas between the track and G (the point at which the response time line for the original base station intersects the response time line for the relocated base station).

Thus, on the whole, the presence of the railroad causes a deterioration in response time for emergency service for the city as a whole.

Ideal Conditions, with Two Base Stations

Let us return to the ideal city shown in Figure 1, and eliminate the assumption that a single base station is needed. We replace this assumption with one that states that two base stations are to be used. Because the objective is still to minimize the maximum response time, the stations should be located such that

1. At the common boundary of their service areas, T is equal for each station. The value of T in the two base station scenario will be different, of course, than the value of T in the single base station scenario.
2. Response time at each of the city limits is T. For this city, the quarter points ($C3$ and $C4$, each located one-fourth of the length of the city from the city limits) are the optimal locations, as shown in Figure 3.

In essence, the two base stations simply divide the city in half. It may be proven that point H in Figure 3 is located at

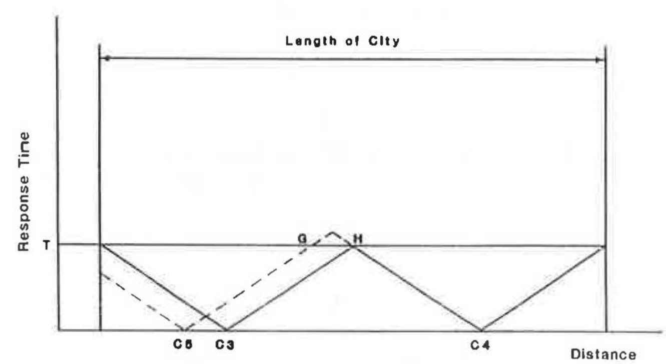

FIGURE 3 Response time versus distance, two base stations.

the center of the city by an approach similar to that used to show that point C in Figure 1 is located in the center of the city. Once it is established that H is located at the center of the city, the proof that $C3$ and $C4$ are located at the quarter points is identical to the proof that point C in Figure 1 is located at the center of the city.

Relocation of either base station will result in a response time exceeding T for some locations in the city. For example, a relocation from $C3$ to $C5$, as shown in Figure 3, will cause section GH to have response times that are larger than acceptable.

Inclusion of RHGCs

If, under the two base station scenario described above, a single-track railroad is assumed to cross the linear city at a point J located between the two base stations, and if it is further assumed that this railroad causes a delay of d for each emergency vehicle attempting to cross it, the condition shown in Figure 4 results. Figure 4 is quite similar to Figure 2, of course; the only difference is in the number of stations, and in the magnitude of the changes required to recalibrate the system.

Because there are four service area endpoints (two per service area), each needs to accommodate one-quarter of the delay d caused by the track. Thus, T will increase by $d/4$. Each base station will shift as follows:

$$s = v(d/4) \tag{3}$$

The new maximum response time is greater than the original maximum response time by $d/4$ in each station's service area. Thus, the presence of the RHGC causes a deterioration in response time not just for the area on the distant side of the RHGC from the station, nor just for that particular station's service area, but for the city as a whole. The only exceptions to this deterioration are some locations in the immediate vicinity of the relocated base stations; these locations will actually have decreased response times.

General Conditions for Linear City

It can be shown mathematically that, for n base stations, the optimal spacing between base stations is L/n, with the distance from the edge of the city to the nearest base station being given by $L/2n$. In addition, the shift toward a single RHGC by each base station in order to correct for a delay of d is

$$s = vd/2n \tag{4}$$

where all variables are defined as before. In addition, the change in maximum response time zT will be

$$zT = d/2n \tag{5}$$

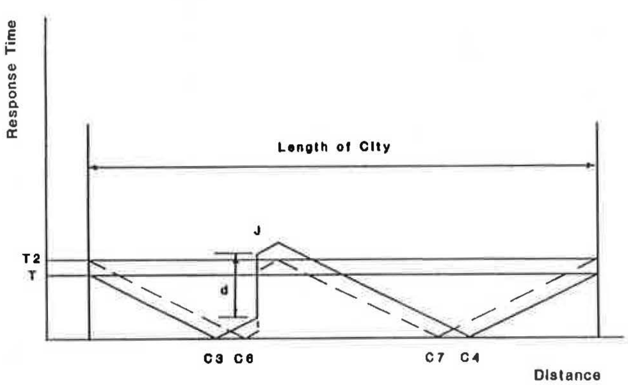

FIGURE 4 Response time versus distance, two base stations with RHGC.

MODEL EXTENSION: TWO-DIMENSIONAL CITY CONDITIONS

The preceding discussion is limited, of course, by the assumption that the city is linear. (It is also limited by the assumption that base stations can be instantaneously relocated, and that the demand for emergency services is uniformly distributed across the city. However, these assumptions are held for the following discussions as well.)

Conditions Without RHGCs

Let us now assume that the city in question is two dimensional; that is, having length and width but not height. Let us further assume that this city is not a transportation surface, but has a right-angle grid street system, and that this grid has been laid out such that each block in the grid is a square. Intersections are assumed to have no impact on response time, even if a turn is involved. All streets are two-way, and each block requires x units of time to traverse. Finally, let us assume that driveway entrances to the street network can be made only at the middle of a block, and that the maximum tolerable response time T is equal to $3.5x$ time units. (The coefficient 3.5 is arbitrary, and has been chosen for ease of presentation.)

Figure 5 shows these conditions and the service area for a single base station located at A. The service area thus defined is a diamond, with a triangular area equivalent to ¼ block

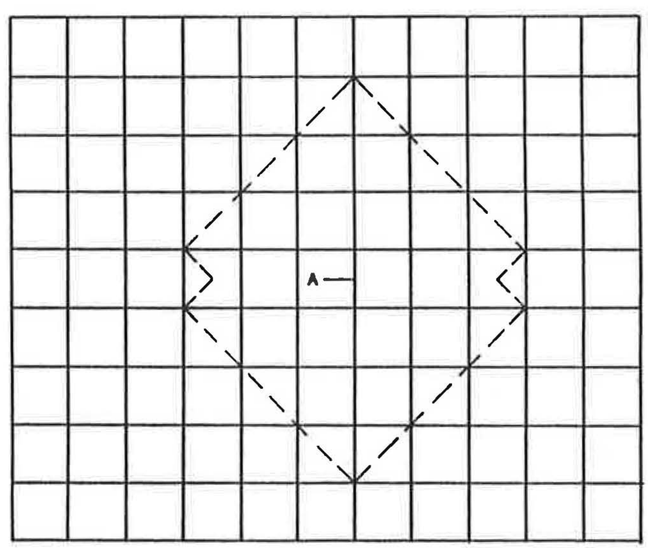

FIGURE 5 Service area boundaries with midblock entrance.

missing from each of the two points of the diamond on the axis at a right angle to the orientation of the access roadway for the station.

These triangular indentations pose a problem in efficient allocation of stations while fulfilling the objective function that $3.5x$ is the maximum acceptable response time. As Figure 6 shows, if the sides of the diamond are used as the boundaries between adjacent service areas, four stations will surround a small diamond that has an area equal to one block, and in which response times are greater than $3.5x$ by, at most, one time unit. Of course, the problems posed by this small diamond can be solved by locating the stations closer together or by redefining the maximum acceptable response time as $4.5x$. In either of these cases, however, the long sides of each service area will have response times less than T, thus resulting in an inefficient use of resources.

The cause of the triangular indentations in each station's service area is the assumption that entrances to the roadway network can occur only at midblock. If this restriction is lifted, and entrances to the network are permitted at intersections, the service areas for $T = 4x$ shown in Figure 7 result, and the indentation problem disappears. (The coefficient has been changed in order to allow service area boundaries to occur at intersections.) For simplicity in modeling the impacts of RHGCs, only this latter access scenario is considered in the following discussion.

Conditions With RHGCs

Let us now consider RHGCs in this analysis, again assuming that every emergency vehicle is delayed for a time period d at each RHGC. The impacts of RHGCs on emergency access are entirely dependent on the location and orientation of a rail line relative to the boundaries of each station's service area. For example, a rail line such as that shown in Figure 8 will have absolutely no impact on emergency access, because the rail line runs along the boundaries of service areas. Thus, no emergency vehicle needs to cross an RHGC. (In fact, this is a method used in practice quite frequently by providers of emergency services; service area borders are often defined by geographical barriers, such as rail lines or rivers.)

A rail line oriented as shown in Figure 9, however, will have a profound impact on emergency access. This line intersects each service area boundary at a 45-degree angle. Furthermore, because the line runs along one street in the right angle grid, there is no simple way to avoid it. Service areas could be redefined to set the track as a boundary, but this would result in inefficient shapes for those service areas abutting the track.

For ease of presentation, let us assume that $d = x$. The hatched areas in Figure 9 are those that can no longer be served within $T = 4x$, with all stations in their original optimal location. Assuming that no stations to the left of the track are relocated, the $T = 4x$ criterion can be met efficiently if all stations to the right of the rail line are moved a distance

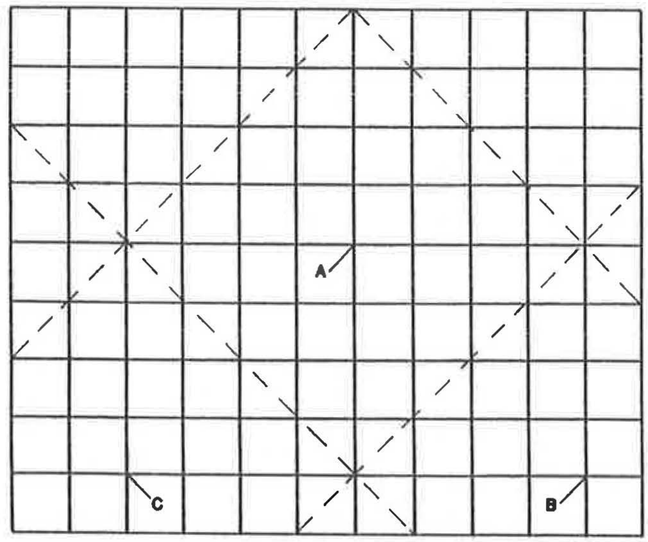

FIGURE 7 Multiple service area boundaries with intersection entrances.

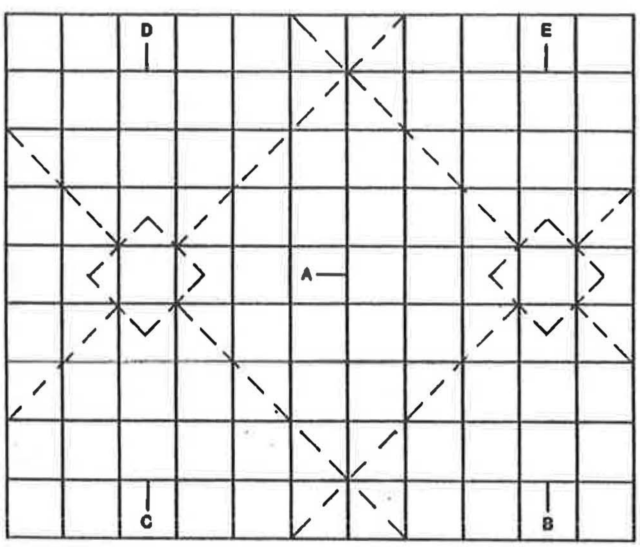

FIGURE 6 Multiple service area boundaries with midblock entrances.

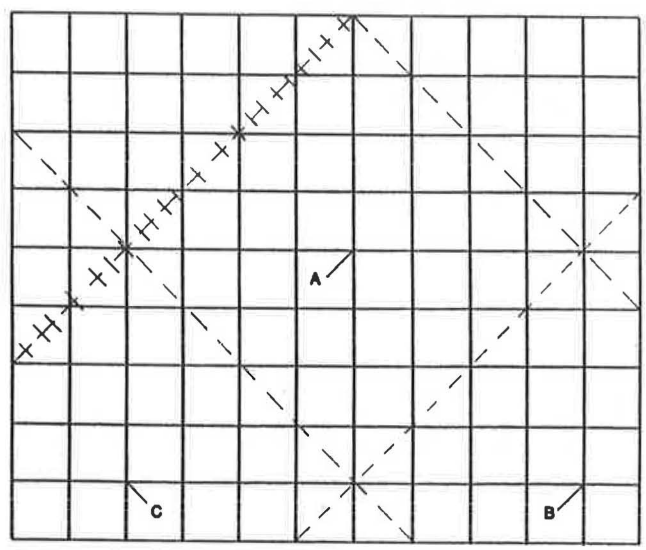

FIGURE 8 Rail line along service area boundaries.

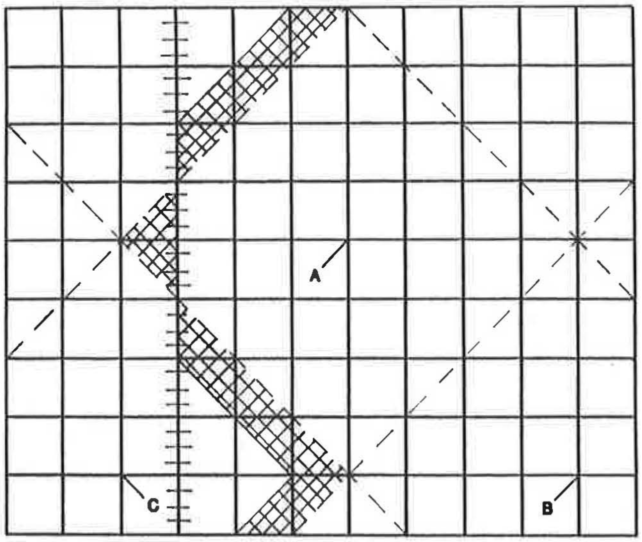

FIGURE 9 Rail line at angle to service area boundaries.

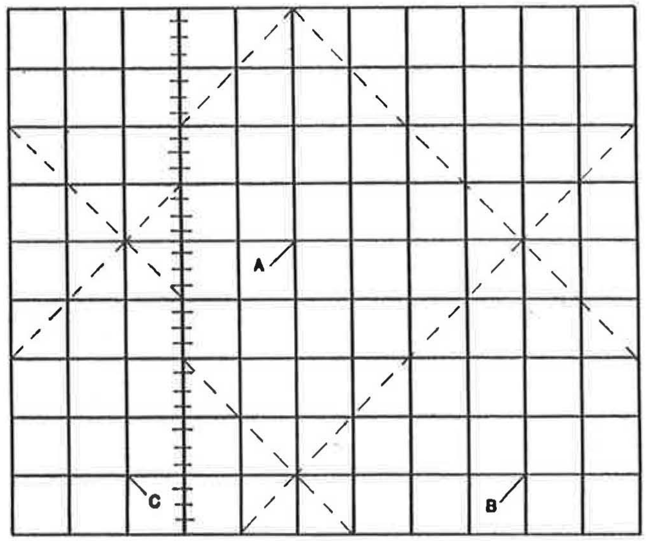

FIGURE 10 Relocation of base stations to right of rail line.

d closer to the rail line. This condition is shown in Figure 10. Of course, the shapes of the service areas through which the rail line extends are no longer diamonds. In addition, such a simplistic decision to shift all stations on one side of the RHGC ignores the system-wide effects. Recall that, in a linear city, all stations would be relocated to equalize the additional travel time through the system. Ideally, the same strategy should be followed in a two-dimensional city; however, unless each station moves a whole number of blocks, the stations will not access the grid network at intersections, resulting in inefficiencies, as described earlier.

As the preceding discussion indicates, the presence of a rail line through a two-dimensional city has the potential for causing severe complications in efforts to optimize the system.

Effects of Grade Separations

Let us now modify the type of system shown in Figure 9 to allow for a grade separation at G, as shown in Figure 11. The presence of this grade separation allows an emergency vehicle to bypass a blocked RHGC. Of course, the advisability of such a bypass depends on the relationship between the length d of the blockage and the time required to divert the emergency vehicle to the grade separation and back to the desired route. Clearly, unless the diversion time is less than d, there is no point in diverting the emergency vehicle.

If d is actually so large that it is advisable to use the grade separation in all cases, the portion of the service area for which $T \leq 4x$ is reduced, as shown by the dashed line in Figure 11. (Factors that could make d very large include a derailment, an accident at an RHGC, and switching operations.) In the event of such a long blockage, the grade separation at G becomes, in effect, a second base station for the area to the left of the track. That is, all emergency vehicles destined for this area must pass through point G, $2x$ time units after leaving the actual base station.

From the preceding discussion, it is clear that if a grade separation is available within a service area, the ideal location

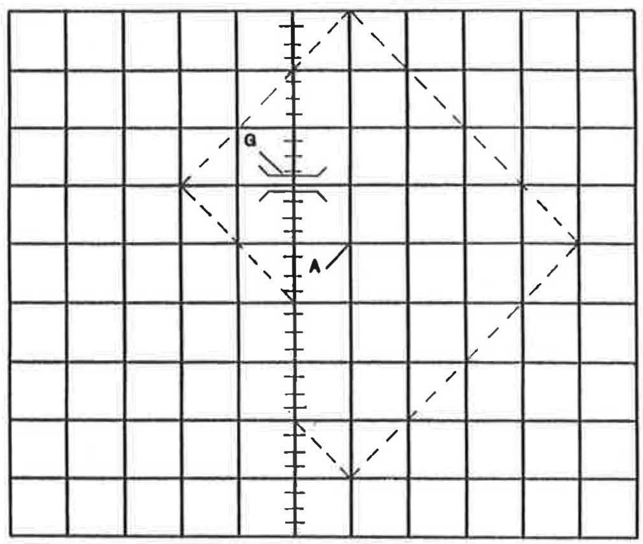

FIGURE 11 Grade separation at G.

for it is immediately adjacent to the base station. This location would eliminate the problem of travel time to the secondary base station. Thus, in Figure 11, under ideal circumstances, the service area would be shifted upward and to the left by one block.

SUMMARY

Given a city in which the demand for emergency services is uniformly distributed, and in which emergency vehicles travel at a uniform speed of v, the following conclusions may be drawn from the preceding discussion:

1. In a linear city of length L, n base stations should be optimally located such that L/n is the spacing between stations, and such that $L/2n$ is the distance from the edge of the city to the nearest base station.

2. In the same linear city, the presence of a rail line that causes a delay of d to all emergency vehicles can most optimally be addressed by moving all base stations by $vd/2n$ closer to the rail line. The maximum response time T will increase for each service area by $d/2n$.

3. In a two-dimensional city with a right angle grid roadway network, the optimal location for emergency vehicle access to any given block is at a corner. Midblock access results in inefficient station locations or in sections of the city not being served within time T.

4. In the same two-dimensional city, the impact on emergency access of the presence of a rail line is entirely dependent on the orientation of the rail line relative to service area boundaries. If the rail line runs along service area boundaries, there is no impact on emergency access. If the rail line cuts through service areas, however, significant impacts may result. If the rail line runs parallel to one of the axes of the grid, the system-wide impacts and optimal strategy to address those impacts are the same as for the linear city. However, the need to have base stations access the network only at intersections complicates implementation of this strategy.

5. The use by emergency vehicles of a grade separation at a random location within a given service area, in effect, results in a second base station. The optimal location for a grade separation is adjacent to the base station, so that the second base station impacts disappear.

SUGGESTIONS FOR FURTHER MODEL EXTENSION

There are, of course, numerous potential extensions of the model that are suggested, as follows:

Traffic Engineering Extensions

These potential extensions involve the inclusion of traditional traffic engineering parameters in the model. For example, the imposition of penalties in response time due to required turns or the presence of intersections would be useful. The model could also be expanded to three dimensions by consideration of roadway grades. In addition, explicit recognition that RHGCs are not always blocked by trains (and thus do not always delay emergency vehicles) and consideration of the stochastic nature of blockage times would enhance the model.

Basic Parameter Extensions

Perhaps the most interesting extension of the basic model would be one that recognized that demand for emergency services is not uniform across a service area, but rather varies in density. It should be noted, however, that such an extension is pointless under the original goal of minimizing maximum response time; the extension would have to include modifying the goal so that average response time is to be minimized.

Combination with Other Models

The basic model presented in this paper assumes that the locations of all RHGCs and grade separations are fixed; the only variable is the location of a given base station.

It would be useful if this model could be used in conjunction with other transportation planning models to determine the societally optimal locations for base stations, RHGCs, and grade separations. For example, construction of a grade separation only one block away from its originally proposed location might reduce emergency access costs substantially, while increasing construction costs and costs to normal roadway users only minimally.

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