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# Scheduling Truck Shipments of <br> Hazardous Materials in the Presence of Curfews 

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#### Abstract

Locally imposed curfews have been considered as a mechanism for reducing risks associated with movements of hazardous materials through heavily populated areas. However, the imposition of such curfews creates scheduling problems for carriers and the need for consideration of overall policy at the state and federal levels. Simple algorithms for addressing these scheduling issues are presented; their use in doing sensitivity analysis of a hypothetical problem involving shipment of spent nuclear fuel by truck is demonstrated.


Transportation of hazardous materials is an issue of considerable public concern. This concern is most sharply focused when the materials being transported are radioactive, but a wide variety of toxic and flammable chemicals also presents varying degrees of risk to people and property. In the United States, most hazardous materials are moved by truck or rail, and these movements frequently pass through heavily populated urban areas.

The mechanisms used to reduce the risks associated with hazardous materials movements include attempts to reduce both the probability of accidents involving these shipments and the number of people potentially exposed to the consequences of an accident, should one occur. In practice, this has led to consideration of restricting hazardous materials to certain specified routes, restricting their movement during some portions of the day (e.g., rush hour), or both.

Regulation of hazardous materials transportation occurs at the local, state, and federal levels. These regulations are in many cases implemented independently, and in some cases they conflict with each other. This has led some observers and partici-

[^0]pants in the industry to criticize the hodgepodge of local regulations, while others defend the rights of local governments to control movements within their jurisdictions.

The focus of this paper is on one important type of movement restriction: the imposition of time-ofday curfews by localities. The objective is to develop analytical tools that can be used for two basic purposes:

1. For a carrier of hazardous materials facing a particular set of curfews in specific cities, an important operational problem is to schedule shipments to minimize total transit time, including delay due to the curfews.
2. For policy analysis, it is important to be able to estimate the total delay imposed by curfews of various types in different numbers of cities in order to determine the aggregate effect of the pattern of local regulations.

Use of the models developed here for operational planning by carriers is important because en route delays imposed by curfews are clearly undesirable. Such delays increase the cost of shipment and, because they increase total time en route, they also increase some elements of risk associated with hazardous materials movement.

To minimize total in-transit time, the carrier may change the departure time of the shipment or the actual route the shipment takes. In the next two sections, methods are developed for optimizing departure times, given a fixed route. In the section Curfew Delay Under Fixed Routing and Deterministic Travel Time, the simplest version of the problem is discussed, that is, the version in which times are assumed to be deterministic. In the section stochastic Intercity Travel Times, the analysis is extended to address uncertain travel times. An example application of these methods to sensitivity analysis of a hypothetical problem of moving spent nuclear fuel assemblies is presented in the third section.

Use of these tools in policy analysis is important because the Hazardous Materials Transportation Act places responsibility on the U.S. Department of Transportation to ensure that local regulations do not impose an unreasonable burden on interstate commerce. Federal officials and various carrier organizations are interested in determining the inconsistency of the curfew restrictions, that is, whether these curfews unreasonably burden commerce. To do this, it is important to determine the effects of curfews on both routing and scheduling decisions, in an aggregate sense.

In this paper, scheduling decisions are addressed. In a subsequent paper, the authors will address combined routing-scheduling analyses. Given a set of origins and destinations for shipments and a set of jurisdictions imposing curfews, combined routingscheduling methods will estimate various measures of risk, total delay, additional miles traveled, and changes in the temporal and spatial pattern of movements.

## CURFEW DELAY UNDER FIXED ROUTING AND DETERMINISTIC

 TRAVEL TIMEIn this section, discussion is presented about how a carrier should operate to minimize its delay time, given no opportunity to reroute to avoid curfews and given no unexpected changes in its travel time along the route. The important point to note is that, given a departure time, an optimal strategy that minimizes total in-transit delay time is to delay a shipment only when it is about to violate a curfew and to delay it only until the curfew passes. This is an intuitive result, for which the formal justification is given by Cox (1).

Because this intuitive procedure yields the minimum delay solution for any specified departure time, the departure scheduling problem can be solved by a simple enumeration scheme. To demonstrate the idea, consider a hypothetical route containing five cities with curfews. For simplicity in this example, it will be assumed that all cities have identical curfews: 7:00 a.m. to 1l:00 a.m. and 3:00 p.m. to 7:00 p.m.

This sort of curfew pattern is the type proposed by Rhode Island for liquid nitrogen gas (LNG) and liquid petroleum gas (LPG) tanker movements (2). However, many other patterns are possible. The method for shipment scheduling described here works under any arbitrary curfew pattern, and different cities along the route need not have the same pattern.

For this example, assume that travel times (in hours) between cities are as shown along the links in Figure 1. Suppose the shipment leaves the origin at 7:00 a.m. It will arrive at City 1 at 12:30 p.m.,
which is an acceptable time to pass through City 1 , and proceed to City 2, arriving at l:30 p.m. City 2 is also passed without delay, and the shipment arrives at City 3, 2 hr later, at 3:30 p.m. Because this arrival time is during City $3^{\prime}$ s curfew, the shipment must wait until 7:00 p.m. before passing tinrouy̆́ City 3, a delay of 3.5 his. Leaving City 3 at 7:00 p.m., the shipment arrives at City 4 at 11:30 p.m= and at city 5 at 4:00 a.m. the following morning. It may then proceed to its destination. Thus, the total delay is 3.5 hr , incurred entirely at City 3.

Suppose the departure had been delayed 1 hr , to 8:00 a.m. Arrival at Cities 1,2 , and 3 would also be delayed 1 hr , but the shipment would still miss the curfews at City 1 and City 2. Because arrival at City 3 would now be at 4:30 p.m. instead of $3: 30$ p.m., delay would be 2.5 hr instead of 3.5 hr , with a departure at 7:00 p.m. as before. Because the shipment departs from City 3 at the same time, the subsequent portion of the trip is unaffected, and it can be concluded that total delay en route is reduced by 1 hr . This delay can be reduced further through postponement of the departure time until 8:30, at which point the shipment encounters the curfew at City 2 (arriving at 3:00 p.m.), and is delayed for 4 hr .

By repeating this analysis for various possible departure times, a graph can be developed of delay with respect to departure time; such a graph is shown in Figure 2. From Figure 2 departure time can be optimized to minimize total en route delay. Note that substantial gains can be made by judicious choice of departure time. Scheduling departures for 6:00 a.m. or 5:30 p.m. results in no delay, whereas departing at 9:30 a.m. results in 8 hr of delay time ( 17.5 hr of aotual travel time).

The simple enumeration analysis just described can be implemented easily on a personal computer, so that the type of diagram shown in Figure 2 can be produced in a matter of seconds, given basic information about the route to be followed and the curfew restrictions in force. The diagram is therefore a potentially useful tool for guiding dispatching decisions.

However, this departure time analysis is limited because intercity travel times for hazardous materials shipments have a large random component that cannot be ignored in scheduling decisions. Notice in Figure 2 that local minima and maxima of en route delay with respect to departure times are adjacent to one another. If a shipment were to depart at 5:30 p.m., expecting to incur no curfew delay, and be unexpectedly delayed for an hour sometimes before it arrived at City 4, it would be delayed an additional 7 hr because of curfews.

A method by which this uncertainty may be addressed is presented in the next section.

## STOCHASTIC INTERCITY TRAVEL TIMES

If travel times have some random component, a recursion may be derived to estimate the expected delay given the departure time of the shipment and a probability distribution for intercity travel times.

Consider a fixed route with $N$ curfew cities along it. The expected value for curfew delay for any departure time is the expected value, taken over all curfew cities $n=1,2, \ldots, N$, of the conditional


FIGURE 1 Travel times (in hours) for example problem.


FIGURE 2 Curfew delay as a function of departure time.
expected delay, given that the shipment first encounters a curfew at City n.

Formally:
$E D(t)=\sum_{n=1}^{N} p(n, t)[d(n, t)+s(n, t)]$
where

$$
\begin{aligned}
E D(t)= & \text { expected delay for departure time } t ; \\
p(n, t)= & \text { probability that first curfew encountered } \\
& \text { after departure time } t \text { is at City } n ; \\
d(n, t)= & \text { expected delay at City } n, \text { given that } \\
& \text { original departure is at } t \text { and that ship- } \\
& \text { ment arrives at } n \text { during its curfew; and } \\
s(n, t)= & \text { expected delay encountered in all cities } \\
& \text { subsequent to } n, \text { given that City } n \text { curfew } \\
& \text { is encountered after initial departure } \\
& \text { at } t .
\end{aligned}
$$

After City $n$ 's curfew is encountered, all shipments must wait until the curfew passes before continuing, independent of when during the curfew they arrive. Thus, $s(n, t)$ is only dependent on $t$, the original departure time, if multiple curfew periods exist during each day.

The expected delay after City $n$ 's curfew is encountered is the expected value, taken over all Cities $m>n$, of the conditional expected delay associated with encountering City m's curfew next:
$s(n, t)=\sum_{m=n+1}^{N} P(n, m, t)[D(n, m, t)+s(m, t)]$
where $P(n, m, t)$ is the probability that the next curfew encountered after $n$ is at City $m$, when original departure is at time $t$; and $D(n, m, t)$ is the expected delay at City $m$, given that the original departure is at $t$ and the last curfew encountered is at City $n$.

Equations 1 and 2 may be solved recursively. Beginning with the origin ( $n=0$ ), one can compute $p(n, t), d(n, t)$, $P(n, m, t)$ and $D(n, m, t)$ for $n<m<N$ and $n=0,1,2, \ldots, N$. Then, $S(n, t)$ can be computed by using the recursive formula (Equation 2), and finally ED( $t$ ) can be computed using Equation 1.

The most difficult part of this calculation is the determination of the probability distribution of arrival time at City $m$, given a departure time from City $n$. This is necessary to compute $P(n, m, t)$ and $D(n, m, t)$. Because several cities may exist between $n$ and $m$, one must either specify directly the distribution of travel times between each pair of cities, or calculate a convolution of travel times across individual links. The authors have implemented the algorithm in BASIC on an IBM personal computer by using a numerical approximation to the convolution
of individual link travel time distributions to calculate $P(n, m, t)$ and $D(n, m, t)$.

As an example of the random travel time model, consider the same problem solved deterministically in the section on Curfew Delay. For the stochastic analysis, the fixed travel times are replaced with probability distributions of travel times on each link. For purposes of example, the simple threepoint discrete distributions shown in Figure 3 have been used. In each case, the expected travel time from the distribution is the same as the deterministic travel time assumed in the first section.
a) Link O-1

b) Link 1-2

c) Link 2-3
d) Links 3-4, 4-5


FIGURE 3 Travel time probability distributions used in example.

Figure 4 shows the results of the stochastic analysis of departure scheduling superimposed on the deterministic results from Figure 2. The random travel time analysis indicates that the best departure times are not as good as the deterministic model predicts, and that the worst times are not as bad. For example, the deterministic analysis indicates that a departure at 5:30 p.m. would result in arrival times at the cities as follows:

| City | Arrival Time |
| :---: | :---: |
| 1 | 11:00 p.m. |
| 2 | 12:00 midnight |
| 3 | 2:00 a.m. |
| 4 | 6:30 a.m. |
| 5 | 11:00 a.m. |

Note that the shipment is scheduled to arrive at City 4 before the beginning of the morning curfew, and at City 5 after the end of its morning curfew. The analysis indicates a window of one-half hour during which there is no delay. This corresponds to the available time from 6:30 a.m. to 7:00 a.m. to get


FIGURE 4 Comparison of expected curfew delay for deterministic and stochastic analyses.
through city 4 before the morning curfew. If the shipment is delayed at City 4 until the end of the morning curfew at ll:00 a.m., it will be delayed again at city 5 during the afternoon curfew.

The stochastic analysis indicates that there is some expected delay for even the best departure times because some chance of delay exists before getting to City 4. It also indicates that there is a broader window over which expected delay changes relatively little ( $4: 00 \mathrm{p} . \mathrm{m}$. to $5: 30 \mathrm{p} . \mathrm{m}$.$) , and that$ this window is earlier than indicated by the deterministic analysis.

The wider departure window is due to the increasing uncertainty of arrival times for points farther along the route. It is difficult to plan a departure for a precise arrival time at a city that is, on average, 13 hr away. The uncertainty inherent in predicting travel times over long distances means that precise departure scheduling is not as important as implied by the deterministic model.

That the optimal departure times in the stochastic analysis are earlier than in the deterministic analysis is a reflection of the skewness assumed in the travel time distributions. Delays cause larger deviations from average travel times than do early arrivals. Thus, the statistical analysis indicates that it is wise to build some additional slack time into the schedule to accommodate those possible delays. In this example, if travel times run according to plan, a departure at 4:30 p.m. would encounter 1 hr of delay at City 5. However, 1 hr of extra slack exists to absorb delays before City 4 , without getting caught during the morning curfew there; with attendant additional delays at City 5 during the afternoon.

Comparative analysis of this one simple example is insufficient as a basis for making extensive conclusions. However, these three main differences are intuitively reasonable, and should apply broadly. The implications for scheduling shipments are that precision is not as important as might be indicated by the deterministic model, and that the optimal departure time is likely to be earlier than indicated by the deterministic model.

## SENSITIVITY ANALYSIS IN AN EXAMPLE APPLICATION

The transport of nuclear materials has been a topic of recent administrative rulings, court cases challenging those rulings, and congressional action. The highway transport of spent nuclear fuel in particular has been controversial. Spent fuel elements are highly radioactive and contain long-lived radioactive isotopes and transuranics, including plutonium. These wastes are currently stored at reactor sites, but the fuel pools are being filled rapidly and were never designed for permanent waste storage. The National Waste Policy Act (42 U.S.C. sec. 10222
et seq.; see also 10 C.F.R. sec. 961) requires the U.S. Department of Energy to designate one or more permanent repositories for such wastes.

This example addresses the problems of scheduling truck shipments of commercial spent fuel on the Interstate highway system, in particular focusing on the changes in the curfew delay incurred by a spent fuel shipment as the following characteristics of the curfew pattern and the shipment change:

- Length of the curfew
- Type of curfew (all day or peak period only)
- Number of jurisdictions imposing curfews
- Whether the departure times of shipments are scheduled to minimize curfew delay
- Variance associated with travel time

The example is a hypothetical one involving shipments from a single reactor to a single permanent repository, with a set of 11 cities imposing curfews en route. The data for this example apply to a particular reactor and potential repository site in the eastern United States, but the actual identity of the sites is not important for the purposes of this paper, and this example is not intended to represent a complete analysis of this route.

## Deterministic Travel Time Analysis

The graphic procedure presented in the first section to estimate delay as a function of departure time was applied to this route, assuming that each city imposes the same curfews (7:00 a.m. to 11:00 a.m. and 3:00 p.m. to 7:00 p.m.). The results are shown in Figure 5 as a graph of delay versus departure time. Note the characteristic sawtooth pattern resulting in delay estimates ranging from 14.5 hr when departing at 5:30 a.m. to 1.5 hr when departing at $10: 30$ p.m.

By varying the length of the peak-period curfew, the sensitivity of average and minimum delays to changes in this value can be explored. The results are given in Table l. By repeating the analysis with a single-period curfew, the delay time estimates presented in Table 2 are obtained. Note that under both types of curfew, the average and minimum delays increase approximately quadratically as the length of the curfew increases. Also note that the delay under peak-period curfews is substantially less than that under single-period curfews of the same total length. This is because the peak-period curfews allow a window of travel during midday.

By randomly assigning a subset of the cities to impose a 7:00 a.m. to 11:00 a.m. and 3:00 p.m. to 7:00 p.m. curfew, with the remaining cities imposing


FIGURE 5 Curfew delay as a function of departure time-fixed route.

TABLE 1 Length of Peak-Period Curfew Versus Average and Minimum Delays

| Curfew Period | Average Delay over All Departure Times (hr) | Minimum Delay over All Departure Times (hr) |
| :---: | :---: | :---: |
| $\begin{aligned} & \text { 6:00 a.m.-11:00 a.m. } \\ & \text { 3:00 p.m.-8:00 p.m. } \end{aligned}$ | 12 | 4.5 |
| $\begin{aligned} & \text { 7:00 a.m.-11:00 a.m. } \\ & \text { 3:00 p.m.-7:00 p.m. } \end{aligned}$ | 7.7 | 1.5 |
| $\begin{aligned} & \text { 7:00 a.m. }-10: 00 \mathrm{a} . \mathrm{m} . \\ & \text { 3:30 p.m.-6:30 p.m. } \end{aligned}$ | 4.0 | 1.0 |
| $\begin{aligned} & \text { 7:00 a.m. }-9: 00 \mathrm{a} . \mathrm{m} . \\ & \text { 4:00 p.m. }-6: 00 \mathrm{p} . \mathrm{m} . \end{aligned}$ | 2.0 | 0 |
| $\begin{aligned} & \text { 7:30 a.m.-8:30 a.m. } \\ & \text { 4:30 p.m. }-5: 30 \text { p.m. } \end{aligned}$ | 0.4 | 0 |

TABLE 2 Single-Period Curfew Analysis

| Curfew Period | Average Delay over All Departure Times (hr) | Minimum Delay over All <br> Departure Times (hr) |
| :---: | :---: | :---: |
| 6:00 a.m.-8:00 p.m. | 28.3 | 16.5 |
| 7:00 a.m.-7:00 p.m. | 22.6 | 14.5 |
| 8:00 a.m.-6:00 p.m. | 13 | 5.0 |
| 9:00 a.m.-5:00 p.m. | 10.8 | 3.0 |
| 10:00 a.m.-4:00 p.m. | 5.9 | 1.0 |
| 3:00 p.m.-7:00 p.m, | 2.9 | 0 |
| 4:00 p.m.-6:00 p.m. | 1.1 | - |

no curfew, one can estimate how delay varies with the number of cities imposing curfews on the route. The results are shown in Figure 6. On this scatterplot, each point represents the average curfew delay with a random subset of cities imposing curfews on the route, where the number of cities in the subset is plotted on the x-axis. Note that the relationship between delay and the number of cities with curfews is approximately linear. However, for any given number of cities imposing a curfew, the variance in total shipment delay is large, indicating that the total delay is sensitive to which cities impose curfews.


FIGURE 6 Delay versus number of cities imposing curfews.

## Results for Stochastic Travel Times

To compute the delay under stochastic travel times, the recursion formulas discussed in the section on Stochastic Intercity Travel Times were used. Assuming a curfew of 7:00 a.m. to 11:00 a.m. and 3:00 p.m. to 7:00 p.m. for all cities, Figure 7 shows delay as a function of departure time for three different values of intercity travel time variance. The first point


FIGURE 7 Curfew delay profile as variance of travel time changes.
to note is that for the zero-variance case, the delay function is the same as the one shown in Figure 5, as expected. Second, note that as the variance increases, the difference between minimum and maximum delay is reduced, and the profile becomes smoother. This is to be expected; as travel times grow more uncertain, it becomes less likely that either the best possible outcome (minimum delay) or worst possible outcome (maximum delay) will be observed. Thus, the expected delay becomes less sensitive to the actual departure time of the shipment. Last, note that the local minima of the delay profile move to the left as variance increases. As variance increases, it is more likely that a shipment will be delayed unexpectedly. If a shipment departed during the zero-variance delay minimum, such as at 10:30 p.m., a good chance exists that the actual delay would be as though it left at 11:00 p.m., which is a local maxima, because it is more likely that travel time will be longer than expected rather than less than expected. It is wiser, in the case of uncertain travel times, to depart earlier to account for the expected values of delays. Thus, the minima for scheduling departure times should move to the left.

## SUMMARY

In the first section on Curfew Delay, it was argued that the natural approach to delaying a shipment along a route in the face of curfews was the optimal strategy to minimize total curfew delay. As a result, given a departure time and intercity travel times, the delay time may be estimated using a simple enumeration. In the section on Stochastic Intercity Travel Times, a recursive procedure was presented for estimating expected delay, given a departure time, for random travel times.

The major implications of uncertain travel times in the analysis are as follows:

1. It is unreasonable to expect delays as small as those indicated by optimal deterministic solutions;
2. As uncertainty in travel times increases, the relative advantages of precise dispatching decrease;
3. Whe optimal departure time when travel times are uncertain is earlier than when they are assumed to be known with certainty.

The important benefits from the models described in this paper are that they are relatively simple; require modest amounts of data; can be operated easily on a personal computer; and can provide estimates of how much delay can be expected, how important precise departure scheduling is, and what are the best departure times in a given situation.

In the third section, a hypothetical example was presented of spent nuclear fuel shipments between one specific reactor and a single potential permanent spent fuel repository. The purpose of this ex-
ample is to demonstrate how the models developed in this paper can be used to do sensitivity analysis on various elements of hazardous materials routingscheduling problems. It should not be construed as a complete analysis of the effects of curfews on hazardous materials movement. The authors believe, however, that it does demonstrate the usefulness of these analytic tools in addressing several important issues in hazardous materials transportation.

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