Florida DOT Pontis User Cost Study

Final Report

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Executive summary

The Florida Department of Transportation is implementing the AASHTOWare Pontis Bridge Management System (BMS) as a decision support tool for planning and programming bridge maintenance, repairs, rehabilitation, improvements, and replacement for more than 6,000 bridges on the state highway network. A BMS stores inventory and inspection data in a database, and uses engineering and economic models to predict the possible outcomes of policy and program decisions.

User cost models are used in Pontis to quantify, in economic terms, the potential safety and mobility benefits of functional improvements to bridges. The Pontis user cost model estimates the user benefits of three types of functional improvements:

- Bridge widening, which primarily affects accident risk on the roadway carried by the bridge. The addition of new lanes to increase capacity is not addressed in this model since it is closely tied to the widening of the approach road, which is beyond the scope of the BMS.
- Bridge raising, which affects the ability for tall trucks to pass under the bridge. The user cost model predicts the potential savings in truck detour costs.
- Bridge strengthening, which affects the ability for heavy trucks to pass over the bridge. Here, also, the user cost model predicts the potential savings in truck detour costs.

Almost 15 percent of the bridges on Florida’s state highway system have functional needs according to the Pontis default level-of-service standards.

The Florida Department of Transportation (FDOT) selected the University of Florida, with subcontract support from Paul D. Thompson, to analyze the applicability of the Pontis model to Florida and to customize it as needed so it will work effectively in support of FDOT decision-making. The two-year project included a detailed analysis of the Pontis model, an extensive review of the literature on bridge safety and related topics, a search for Florida-specific data to quantify the model, and development of a new model of accident risk.

An analysis of the Pontis user cost model found that it was overly sensitive to extremes of roadway width, yielding unrealistically high benefit estimates. A new model was developed using Florida data on bridge characteristics and traffic accidents. The new model has superior behavior and statistical characteristics on a full inventory of state highway bridges. The result is the first new model of bridge-related accident risk developed anywhere in the United States in more than 15 years, reflecting the substantial improvements in roadway and vehicle safety that have occurred in that time. Since it relies solely on National Bridge Inventory (NBI) data items, the model is readily transferable to many different Bridge Management Systems.

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1.0 Background

Pontis began as Phase 2 of FHWA Demonstration Project 71 in 1989. Phase 1 of the project had featured a series of workshops attended by 49 states, to discuss states' decision support needs in bridge management and to determine what, if anything, should be done at the national level to try to address these needs (FHWA, 1989). Following completion of Phase 1, the US Federal Highway Administration convened a five-state Technical Advisory Committee (TAC) to develop a generic Bridge Management System (BMS) that might act as a nucleus for BMS implementation efforts nationwide.

In October of 1989, the Committee selected a consulting team, led by a joint venture of Cambridge Systematics, Inc. and Optima, Inc., with subcontract support from The Urban Institute, to develop the system, to be called Pontis. The consulting contract was administered by the California Department of Transportation, which also chaired the TAC. Pontis 1.0 was completed and released to the states as public domain software in January of 1992.

A few months later, a group of thirteen states, including Florida, agreed to beta test the software. Based on the recommendations of the beta-testers, Pontis 2.0, again public domain software, was developed and released in 1994. This contract was again funded by the FHWA, but administered by the Volpe National Transportation Systems Center of USDOT. Cambridge Systematics, Inc. was the contractor. The FDOT representative in the beta testing group was Larry Davis.

Upon completion of Pontis 2.0, responsibility for maintenance and further enhancement moved to the American Association of State Highway and Transportation Officials (AASHTO). AASHTO issued a project solicitation to re-write much of Pontis as a client-server system with a graphical user interface, operable under Microsoft Windows. Although the core analytical models would remain similar to the original concept, the added features would make the software suitable for full-scale implementation in a large organization. A total of 38 agencies, including Florida and FHWA, elected to participate in the project, which resulted in the release of Pontis 3.0 in 1995. This was developed again by the same contractor.

Since that time, Pontis has received further updates, mostly to its graphic user interface and database management capabilities. Version 3.42 was used in the current study. As of this writing, there are 45 licensees of Pontis, including three municipal governments and three transportation agencies outside the United States.

The current study is part of a research program initiated by Bill Amrhein of FDOT in 1996, to assist the Department in the successful implementation of Pontis. The user cost study was started in October of 1997, with the University of Florida as research agency, and Paul D. Thompson as a subcontractor and as Principal Investigator. Thompson had earlier been Project Manager of the Pontis project at Cambridge Systematics. In September of 1998, a companion study was started in order to develop Florida-specific agency cost models for Pontis. An FDOT Oracle implementation of the Pontis database, with many custom software features developed by in-house staff, was completed and rolled out in 1998. FDOT began element-level bridge inspections in October of 1998, and is scheduled to have complete coverage of the state highway system with this inspection methodology in late 2000. At this point, the agency cost study will also be complete, and FDOT will be ready for full-scale implementation of the decision support capabilities of the system. Richard Kerr has been leading the FDOT implementation effort since 1998, and is FDOT Project Manager for this study.

The user cost model in Pontis 3.42 is largely the same model that was included in Pontis 1.0. Many minor changes have occurred over the years, however. With most states focused on the bridge inspection procedure and the maintenance, repair, and rehabilitation (MR&R) model, no state has yet taken a serious critical look at the correctness and suitability of the user cost model. The purpose of the current study is to conduct this critical evaluation and customize the model as necessary to make it work well for FDOT.

The general discussion and mathematical results in this report are intended to stand on their own and be understandable to anyone familiar with the economic evaluation of engineering projects. To enable implementation of the results, all material is closely referenced to the Pontis database schema, and to the National Bridge Inventory (NBI) coding guide. The Pontis database is documented in Appendix B of (AASHTO, 1997). Detailed definitions of all Pontis data items may be found in the Database help file on the Pontis compact disk, which is installed with Pontis. All references to NBI data items are documented in (FHWA, 1994). General background information about Bridge Management Systems may be found in (AASHTO, 1992).

Although the latest Pontis release is 3.42, all current documentation is labelled with older version numbers: 3.2 for the user documentation (AASHTO, 1997), and 2.0 for the technical documentation (Golabi et.al., 1992). The technical documentation of the existing user cost model was found to be incorrect, so section 2 of this report was developed based on the sensitivity analysis process and an examination of the source code of this part of the system.

2.0 Existing Pontis user cost model

Benefits of functional improvements in Pontis are assessed in terms of user cost savings (Golabi, et.al., 1992 and Blundell, 1997). When a deficient NBI approach alignment rating or travel way width exists on a bridge, road users are theoretically subject to higher accident risk. To evaluate a functional improvement or replacement which corrects the deficiency, the user cost model predicts a reduction in accident risk, which then is multiplied by an accident cost to yield a user cost savings. When a bridge has substandard vertical clearance or load capacity, certain trucks are unable to pass on or under the bridge and must detour, thus incurring higher labor costs and vehicle operating costs. The user cost model estimates the volume of detoured traffic and the resulting user cost, which would be avoided if the deficiency were corrected. The total user benefit of the functional needs in a project is therefore:

User benefit

$$B_r = W_c / 100 \times V_{ry} \left(BW_r + BR_r + BS_r \right) \qquad (1)$$

Where:

W_c	is the weight given to user cost benefits, in percent (Pontis cost matrix)
V_{ry}	is the forecast average daily traffic volume for the program year being analyzed (see below)
BW_r	is the annual benefit of widening per unit average daily traffic (calculated below)
BR_r	is the annual benefit of raising per unit average daily traffic (calculated below)
BS_r	is the annual benefit of strengthening per unit average daily traffic (calculated below)

In the notation in all equations in this report, subscripts indicate the level of resolution of the variable, or the entity that the variable describes. These are defined as follows:

b	indicates a bridge attribute (corresponds to the Pontis bridge or inspection event table)
r	indicates a roadway attribute (corresponds to the roadway table)
c	indicates a Cost Matrix parameter, linked to the bridge table by dim1val, dim2val, dim3val, dim4val
p	indicates a Policy Matrix parameter, linked to the bridge table by adtclass, dim2val, dim3val, dim4val
y	indicates a program year within the planning horizon

When a bridge-level attribute is taken from the inspection event table, it is taken from the most recent inspection on the bridge. Approach alignment rating is the only attribute of this type. Variables without a subscript are systemwide parameters found in the Configuration Options table or the Improvement Model Parameters table. Florida uses the default definitions of the Pontis policy dimensions, which are as follows:

Dim1val – district in which the bridge is located
Dim2val – functional class of the roadway on the bridge
Dim3val – ownership of the bridge
Dim4val – national highway system (NHS) status of the roadway on the bridge
Adtclass – the traffic volume class of the roadway on the bridge

Each of the components of this formula is described in the following sections. User cost savings tend to be very high in comparison to agency costs of functional improvements. For example, the Florida database exhibited functional needs with a total cost of $220 million and a total potential user cost savings of $1,040 million per year. In practice, nearly all transportation agencies exhibit decision-making behavior that undervalues user costs, relative to the user cost savings that would be estimated according to sound economic principles, as in Pontis. In order to more accurately model real decision-making behavior, Pontis includes the W_c factor to simulate the typical agency's tendency to under-value user costs. The default value of this weight is, naturally, 100 percent. Since benefits are applied in Pontis primarily as a means of setting priorities, the relative differences in user cost savings among competing projects are more important than the absolute magnitude of the savings. Thus, the effect of the weight on priorities is small. However, the implication for the overall investment level in the bridge infrastructure is substantial.

2.1. Traffic Volume Forecast

Traffic volume is explicitly represented in equation (1) because it is the only part of the model that is sensitive to time during the simulation, for Florida's purposes. Other than traffic volume, the remainder of the model remains constant from one year to the next during the simulation. Pontis does allow level of service and design standards to vary by ADT class, which can change during the simulation. However, Florida is not using this feature.

In a normal multi-year simulation, the traffic volume variable, V_{ry}, is forecast by interpolation for the year of the project from Pontis roadway data items as follows:

Forecast average daily traffic
$$V_{ry} = 0 \qquad \text{if } V_{r0} \le 0 \tag{2}$$
$$V_{ry} = V_{r0} \qquad \text{if } V_{rn} \le 0 \text{ or } Y_{r0} \le 0 \text{ or } Y_{rn} \le Y_{r0} \text{ or } Y \le Y_{r0}$$
$$V_{ry} = V_{r0} \times \left(\frac{V_{rn}}{V_{r0}} \right)^{\left(\frac{Y - Y_{r0}}{Y_{rn} - Y_{r0}} \right)} \qquad \text{otherwise}$$

Where: V_{r0} is the most recent actual traffic volume estimate (NBI item 29, adttotal in the roadway table)
Y_{r0} is the year of most recent traffic volume estimate (NBI item 30, adtyear in the roadway table)
V_{rn} is the forecast future traffic volume (NBI item 114, adtfuture in the roadway table)
Y_{rn} is the year of forecast traffic volume (NBI item 115, adtfutyear in the roadway table)
Y is the current year of the program simulation

Equation (2) shows that, in most cases, Pontis interpolates the traffic volume for the current program simulation year based on a constant growth rate between the most recent ADT and the future ADT provided in the roadway table. If the most recent ADT is missing or zero, the effect is to turn off the entire user cost model. If any other variables needed for the traffic growth calculation are missing, the model uses the most recent ADT, adttotal, directly. However, if all variables except adtfutyear are present, Pontis estimates adtfutyear as adtyear plus the improvement model parameter DefaultADTchange. However, there were no cases in the Florida database where this latter refinement was applicable.

For reasons which have not yet been determined, the "Use current functional needs" flag on the scenario data screen causes the model to ignore the growth information and always use adttotal directly. This appears to be an error, since the intended function of this flag is to prevent the simulation from generating new functional needs after the first year, and not to prevent the correct estimation of benefits in the first year. This question has been brought to the attention of CSI. However, the software was used as-is for the sensitivity analysis.

2.2. Benefit of Widening

Pontis estimates the user benefit of widening as the savings in accident costs. In the Florida database, widening needs represented 898 (95 percent) of the 945 cases, 83.5 percent of the costs, and 99.9 percent of the benefits of the full functional improvement program. The average user benefit of a widening project was $1.2 million per year. The method for estimating accident user costs in Pontis is derived from the North Carolina Bridge Management System, using the following formula:

Benefit of widening
$$BW_r = CA_c (R_r - R'_r) \tag{3}$$

Where: CA_c is the average cost per accident (Pontis cost matrix)
R_r is an estimate of the current annual accident risk per vehicle (calculated below)
R'_r is an estimate of the annual accident risk per vehicle after improvement (calculated below)

This result is calculated only for roadways on a bridge; it is zero for roadways under a bridge. It is also set to zero if $R_r < R'_r$. The parameters R and R' can, in principle, be estimated from actual accident studies when they exist. However, no such studies were found in the literature or questionnaire. The North Carolina system offers an approximate way to estimate R based on bridge attributes as follows:

Current accident risk
$$R_r = 365 \times 200 \times (3.28084 W_r)^{-6.5} [1 + 0.5^{\frac{(9-A_b)}{7}}] \tag{4}$$

Where: W_r is the roadway width (curb to curb) in meters (Pontis roadway table, NBI item 51)
A_b is the approach alignment rating (typically 2-9, Pontis inspection event table, NBI item 72)

If the approach alignment rating is missing, it is taken as zero. It would be more appropriate to take it as 9, so it does not add to the accident risk. If roadway width is less than zero, it is treated as zero. Some of the numeric constants in this formula are user-modifiable in Pontis, in the improvement model parameters table. They are defined as follows, with the Pontis parameter name given in parentheses:

365	is the number of days in a year (not customizable)
200	is a regression constant (AccRiscCoeff)
3.28084	is the constant Pontis uses to convert from meters to feet (not customizable)
6.5	is a regression constant (GAccRiskC)
0.5	is a model specification constant (not customizable)
9	is the highest approach alignment rating (GAccRiskB)
7	is the range of allowed approach alignment ratings (GAccRiskB minus GAccRiskA)

The 200 and 6.5 are regression constants derived from the North Carolina study, so they should be modified only if another statistical analysis of accident data is conducted. The 0.5 constant arose because of the practice in North Carolina of assigning only even numbers for approach alignment ratings. It is not important to the model framework, but must be used with the North Carolina regression constants. The final two constants are artifacts of the NBI approach alignment scale, which ranges from 2 to 9. Assuming that FDOT uses the standard NBI definitions for this data item, there is no reason to change these constants.

The formula for accident risk after improvement is similar to (4), but it depends on the width of the improved roadway.

Improved accident risk
$$R'_r = 365 \times 200 \times (3.28084 W'_r)^{-6.5} [1 + 0.5^{\frac{(9-A_b)}{7}}] \tag{5}$$

Where: W'_r is the improved roadway width (curb to curb) in meters (calculated below)
A_b is the approach alignment rating (typically 2-9, Pontis inspection event table, NBI item 72)

Note that the model assumes no change to the approach alignment rating due to widening. Thus, the approach alignment contribution to accident risk is the same in both the current and improved cases. The improved roadway width depends in part on the length of the bridge. For long bridges, the width depends on design standards for lane and shoulder width. For short bridges, the improved width also may depend on the approach road width.

Improved road width
$$W'_r = \max(SW_r, LW_r) \quad \text{if } L_b < 60 \text{ and } W_r < SW_r \tag{6}$$
$$W'_r = LW_r \quad \text{otherwise}$$

Where: SW_r is the design width (meters) if the bridge is short (calculated below)
LW_r is the design width (meters) if the bridge is long (calculated below)
L_b is the bridge length (meters, Pontis bridge table, NBI item 49)
60 is the length threshold (meters, Pontis improvement model parameter MaxWidenLength)

Design width if short

$$SW_r = 0.9 AW_r \tag{7}$$

Where: AW_r is the approach road width (meters, Pontis roadway table, NBI item 32)
0.9 is the width deficiency factor (Pontis improvement model parameter WidthDefFactor)

Design width if long

$$LW_r = LN_r \times DLW_p + 2 \times DSW_p \tag{8}$$

Where: LN_r is the number of lanes (Pontis roadway table, NBI item 28)
DLW_p is the design lane width (meters, Pontis policy matrix)
DSW_p is the design shoulder width (meters, Pontis policy matrix)

The Florida database did not have any missing values in the columns involved in the improved road width calculation. A review of the source code could not determine what assumptions the software would make in the event of missing data. A total of 671 of the 898 roadways identified for widening had lengths less than or equal to 60 meters.

Pontis has an acc_risk column in the roadway table, intended to hold an externally-calculated value for accident risk. This column is not populated in Florida. A review of the source code indicates that this item is probably not used by Pontis.

Both the accident risk model and the average accident cost take into account all types of accidents: fatal, injury, and property damage. The North Carolina model estimates these separately, but Pontis does not require a distinction among accident types so it combines them.

2.3. Benefit of Raising

The Florida database has 45 cases of raising, accounting for 11.7 percent of the cost but only 0.06 percent of the benefits of the full functional improvement program. The average benefit of a raising project was $14,000 per year. Pontis calculates the vehicle operating cost and travel time cost associated with traffic on a detour route, and assumes that this entire cost is saved if a functional improvement is undertaken. Only trucks are assumed to be affected. Raising is considered only for roadways under a structure. The project benefit is then:

Benefit of raising

$$BR_r = 365 \times DC_r \times PT_r / 100 \times PH_r / 100 \tag{9}$$

Where: DC_r is the detour cost per truck for this roadway (calculated below)
PT_r is the percentage of the traffic stream occupied by trucks (Pontis roadway table, NBI item 109)
PH_r is the percentage of trucks which are detoured by the bridge (calculated below)

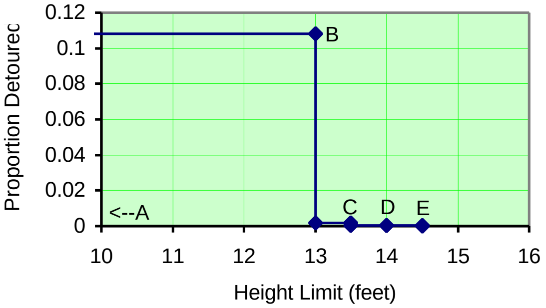
If the truck percentage is missing or zero, it is given the value of the improvement model parameter DefaultTruckPct, whose default value is 5 percent. This affected 21 of the 45 cases of raising in Florida.

Pontis calculates the detoured percentage of trucks by comparing the vertical clearance field (vclrinv in the roadway table, NBI item 10) against a stepwise linear graph of the distribution of truck heights in the traffic stream. Figure 1 shows the default values developed for California. For easier reading, the default values are shown on the graph in feet. However, the values in Pontis are expressed in meters as in the table.

Figure 1. Default truck height histogram

Point	Height Limit (m)	Percent Detoured
A	<= 0.00 (ClrDetoursThreshA)	0.000 (ClrDetoursFracA)
B	<= 3.96 (ClrDetoursThreshB)	10.810 (ClrDetoursFracB)
C	< 4.11 (ClrDetoursThreshC)	0.180 (ClrDetoursFracC)
D	< 4.27 (ClrDetoursThreshD)	0.050 (ClrDetoursFracD)
E	< 4.42 (ClrDetoursThreshE)	0.027 (ClrDetoursFracE)
	.>= ClrDetoursThreshE	0.000 (ClrDetoursDefault)

States may customize this model by modifying any or all of the breakpoints in the improvement model parameters table.



2.4. Benefit of Strengthening

The Florida database has only 3 cases of strengthening, reflecting the fact that the state has only a very small percentage of posted bridges compared to most other states. Strengthening accounted for 4.8 percent of the cost but only 0.03 percent of the benefits of the full functional improvement program. The average benefit of a strengthening project was $93,000 per year. Pontis calculates the vehicle operating cost and travel time cost associated with traffic on a detour route, and assumes that this entire cost is saved if a functional improvement is undertaken. Only trucks are assumed to be affected. Strengthening is considered only for roadways on top of a structure. The benefit is then:

Benefit of strengthening $$BS_r = 365 \times DC_r \times PT_r / 100 \times PW_b / 100 \qquad (10)$$

Where: DC_r is the detour cost per truck for this roadway (calculated below)
PT_r is the percentage of the traffic stream occupied by trucks (Pontis roadway table, NBI item 109)
PW_b is the percentage of trucks which are detoured by the bridge (calculated below)

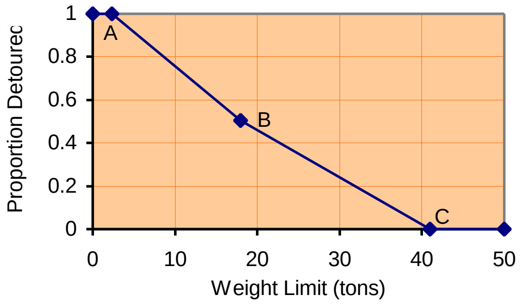
If the truck percentage is missing or zero, it is given the value of the improvement model parameter DefaultTruckPct, whose default value is 5 percent. This affected 2 of the 3 strengthening cases in Florida.

Pontis calculates the detoured percentage of trucks by comparing the operating rating (orload in the bridge table, NBI item 64) against a piecewise linear graph of the distribution of truck weights in the traffic stream, as shown in Figure 2. The agency determines the x-coordinates for the breakpoints at the top and bottom of the graph, and the x,y coordinates for the center breakpoint. The default values were developed for California in 1991. As an example of reading the graph, the center breakpoint specifies that a bridge with an 18 ton weight limit will detour 50.425 percent of the trucks. The table shows default values and names of the customizable parameters in the improvement model parameters table.

Figure 2. Default truck weight histogram

Point	Weight Limit (tons)	Percent Detoured
A	2.3 (StrDetoursMinThresh)	100.0
B	18.0 (StrDetoursCornerX)	50.425 (StrDetoursCornerY)
C	41.0 (StrDetoursMaxThresh)	0.0

Between point A and zero, all trucks are detoured.
At or below zero, no traffic is detoured.
Above point C no traffic is detoured.



It is possible that some fraction of trucks exceeds the operating rating but ignores any posting signs present. Also, many states post bridges at levels different from the operating rating. The model makes no assumptions about these factors, since it describes only the percentage of trucks that are actually detoured at each operating rating level.

2.5. Benefit of Replacement

The sensitivity analysis data set for Florida did not include any replacement projects, since these were filtered out. However, the user cost model for replacement benefits is very similar to the combined effect of all of the separate functional improvements. An analysis of the source code reveals just a few differences as discussed in this section.

When a bridge is replaced, Pontis recognizes the benefits of widening for all roadways on and under the bridge. All roadways are assumed to have the approach alignment rating of the bridge before the project, and all are assumed to have an approach alignment rating of 9 after the project. With these refinements, the user cost formulas are the same as formulas (3) – (8) above.

Pontis assumes that bridge replacement eliminates all operating rating deficiencies. As a result, the project benefit includes the benefit of strengthening, calculated in the same way as described above in formula (10).

Pontis assumes that vertical clearance deficiencies are removed for all roadways on and under the bridge when the bridge is replaced. This properly handles the cases where bridges have restricted vertical clearance on the roadway on top of the structure, such as thru-truss bridges. Florida has 8 bridges in its inventory which have roadways-on with vertical clearances of 14.5 feet or less.

The replacement benefit model for height-related detours in Pontis is formulated to allow for the possibility that, when both height and weight restrictions exist, certain trucks may be affected by both restrictions.

Repl. height benefit
$$BR_r = 365 \times DC_r \times PT_r / 100 \times \left[(1 - PW_b / 100) \times PG_b / 100 \times PH_r / 100 \right] \quad (11)$$

Where: DC_r is the detour cost per truck for this roadway (calculated below)
PT_r is the percentage of the traffic stream occupied by trucks (Pontis roadway table, NBI item 109)
PW_b is the percentage of trucks which are detoured by the bridge due to weight (same as above)
PH_r is the percentage of trucks which are detoured by the bridge due to height (same as above)
PG_b is the percentage of those trucks not detoured by the weight limit, which are potentially subject to height restrictions (explained below)

The proportion of those trucks not detoured by weight limits, that are potentially subject to height restrictions, is given as a piecewise linear graph, as shown in Figure 3. When the weight limit is below the first breakpoint, it is assumed that all traffic is detoured anyway, so height limits are not considered for any trucks. When the weight limit is above the last breakpoint, a constant fraction of the traffic stream is assumed to be potentially subject to height limits. With the default values shown, this fraction is less than 1 because, when this model was developed for California, only duals and tractor-trailers were considered for height restrictions.

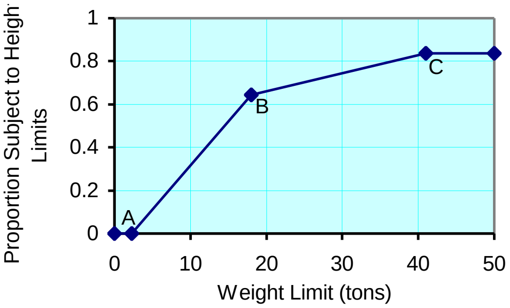
There is a subtle logical inconsistency in the use of PH_r in the raising and replacement models. In the raising model, PH_r is a percentage of the entire truck traffic stream which is detoured, since the percentage detoured by weight restrictions is zero. In the replacement model, on the other hand, PH_r is a percentage of only the lighter-weight duals and tractor-trailers. The (1- PW_b) term restricts PH_r to lighter-weight vehicles, and the PG_b term restricts PH_r to only duals and tractor-trailers.

Part of this inconsistency can be removed by setting all the percentages in the PG_b model to 100, so the definition of PH_r is not limited to duals and tractor-trailers. There is no easy way, however, to remove the effect of (1- PW_b). Fortunately for Florida, the number of bridges with both operating rating of 41 tons or less, and roadway-on vertical clearance of 14.5 feet or less, is zero. Thus, in all cases where PH_r is more than zero, (1- $PW_b/100$) is 1 and no inconsistency exists.

Figure 3. Default proportion of those trucks not detoured by weight limits, that are potentially subject to height restrictions

Point	Weight Limit (tons)	Percent Subject to Height Limits
A	2.3 (MinDualTTST)	0.0
B	18.0 (DualTTSTxA)	64.30 (DualTTSTyA)
C	41.0 (DualTTSTxB)	83.57 (DualTTSTyB)

Below point A no traffic is subject to the height limits
Above point C the proportion remains constant at DualTTSTyB.



Considering the Pontis user community as a whole, it would be worthwhile to consider eliminating the PG_b factor and simplifying the definition of PH_r to conform to its usage in the strengthening model. This could cause some minor double-counting of benefits in cases where both clearance and weight restrictions exist on the roadway on top of a bridge, but the number of cases where this is a problem is likely to be small in most states. The benefit of the change would be to make the user cost model smaller, more consistent, and more understandable.

2.6. Detour Cost

Each time a truck is detoured, it experiences vehicle operating costs associated with the added detour distance, and travel time costs associated with the added detour time. Pontis uses a model of these factors for raising, strengthening, and replacement.

Detour cost per truck
$$DC_r = CV_c \times D_r + CT_c \times \frac{D_r}{DS_r} \quad (12)$$

Where: CV_c is the average vehicle operating cost per km of detour (Pontis cost matrix)
CT_c is the average travel time cost per hour of detour (Pontis cost matrix)
D_r is the detour distance for the roadway in km (Pontis roadway table, NBI item 19)
DS_r is the speed on the detour route, kph (Pontis roadway table, not in NBI)

When the roadway detour distance is less than or equal to zero, it is treated as 1 km. Since detour speed is not an NBI data item, many agencies lack this information. When missing, Pontis estimates the detour speed by factoring the roadway speed (Pontis roadway table), using the improvement model parameter DetspeedFactor. The default value of this factor is 80 percent. Since roadway speed, also, is not an NBI item, Pontis has a set of default speed values DefaultRoadspeedFCnn, where nn is the roadway functional class, in the improvement model parameters table. Since these defaults are very rough, it is better to collect the actual detour speed or at least the bridge roadway speed, if possible. (FDOT is doing the latter as a part of its routine inspections.)

The Florida database lacks both the detour speed and the road speed, so it uses the DefaultRoadspeedFCnn parameters. Only functional classes 09, 11, 14, 16, 17, and 19 have roadways with raising or strengthening needs.

3.0 Sensitivity analysis

The sensitivity analysis was conducted by successive runs of a spreadsheet designed to duplicate the functioning of the user cost model in the Pontis program simulation. Each run featured a single incremental change to the base-case model. Since only functional improvement actions were included, project benefits provided the total measure of user costs. The results of the runs were tabulated and graphed to show the marginal effect of each model parameter.

3.1. Data Preparation

The analysis used the FDOT Pontis database as it existed in July, 1998. This database was in Access 95 format, converted from FDOT"s Oracle implementation of Pontis 3.2. The database contained information about 6,384 Florida bridges, having a total of 8,426 roadway records. Although the database contained condition unit data, there were no preservation models.

The database was upgraded to be compatible with release 3.4, using the procedures documented in the readme.txt and the p34upg_a.txt files provided on the Pontis 3.4 installation CD. The original Access 95 database was upgraded to Access 97, and all required and optional SQL scripts and procedures were executed.

To maximize the usefulness of data from the simulation runs, several default values of Pontis configuration options were changed, as follows:

MRRCOSTINBENEFIT was verified to be set to NO
FIRSTPROGYEAR was set to 1999
KEEPYEAR1NEEDS was set to Y
MINWIDTHDEF was set to 0

These options are explained in the Pontis help system. The first setting ensures that the definition of total benefits is consistent with previous versions of Pontis. The final setting ensures that widening projects are generated even if the magnitude of the deficiency is small. This has the effect of creating a larger set of deficient bridges for which the user cost model can be tested.

3.2. Preliminary Data Analysis

Table 1 lists all of the Pontis data items that participate in the user cost model. The first section of the table shows the data items that are present for each bridge, while the second section shows the model parameters to be analyzed. The table indicates which parts of the user cost model are affected by each item, and the Pontis database table and field where the item can be found.

The database contains 6,384 bridges and 8,426 roadways. Of these roadways, 6,336 are on bridges, and 2,090 are under bridges. Of the roadways under bridges, 183 are the second or subsequent roadways under bridges (for bridges having more than one roadway under them).

As the upper part of Table 1 shows, the database is quite well populated in most cases. Only Detour Speed and Roadway Speed were completely missing. Approach Alignment Rating, Operating Rating, and Future Volume Year are missing in a small number of cases. Traffic Volume Year is missing in a larger number of cases, almost all of which are for roadways under bridges. In general, though, the roadways under bridges are almost as well populated as the roadways on bridges. The Pontis program simulation was run on this entire data set. On the scenario definition screen, the following values were selected:

Table 1. Data used in the analysis

FDOT Bridge Data				Number	Number	Of non-missing values			
Variable	Model	Pontis table	Field name	Missing	Present	Median	Maximum	Minimum	
Functional class (bridge)	All	Bridge table	dim2val (NBI 26)	6	6377	11	19	1	
Detour distance	Detours	Roadway table	bypasslen (NBI 19)	1	8425	1	999	0	
Detour speed	Detours	Roadway table	det_speed	8426	0	N/A	N/A	N/A	
Functional class (roadway)	Detours	Roadway table	funcclass (NBI 26)	10	8416	11	19	1	
Roadway speed	Detours	Roadway table	road_speed	8426	0	N/A	N/A	N/A	
Truck fraction	Detours	Roadway table	truckpct (NBI 109)	2	8424	8	80	0	
Vertical clearance	Raising	Roadway table	vclrinv (NBI 10)	1	8425	99.99	100	0	
Operating rating	Strengthening	Bridge table	orload (NBI 64)	47	6337	58.9	100	2.7	
Future volume	Traffic	Roadway table	adtfuture (NBI 114)	2	8424	25000	538375	0	
Future volume year	Traffic	Roadway table	adtfutyear (NBI 115)	40	8386	2018	2029	2000	
Traffic volume	Traffic	Roadway table	adttotal (NBI 29)	1	8425	13000	648500	0	
Traffic volume year	Traffic	Roadway table	adtyear (NBI 30)	766	7660	1995	2031	1980	Note 1
Bridge length	Widening	Bridge table	length (NBI 49)	2	6381	51.8	10887.5	1.8	Note 2
Approach alignment rating	Widening	Inspection Event table	appralign (NBI 72)	55	6336	8	9	1	
Approach road width	Widening	Roadway table	aroadwidth (NBI 32)	26	8400	12.1	85.3	1.2	
Number of lanes	Widening	Roadway table	lanes (NBI 28)	32	8394	2	84	1	Note 3
Roadway width	Widening	Roadway table	roadwidth (NBI 51)	1034	7398	12	66	1	

NOTES

1. 756 of the missing values were on roadways-under.
2. The data set had 16 bridges with lengths less than 6.1 meters.
3. Five roadways had suspiciously high numbers of lanes, but none of these were in the sensitivity analysis data set.

Model Parameters				Florida	
Variable	Model	Pontis table	Field name	Default	
Detour cost per hour	Detours	Cost matrix	hrdetourco	19.34	Default was the same for all functional classes
Detour cost per km	Detours	Cost matrix	kmdetourco	0.25	Default was the same for all functional classes
Default road speed, FC 1	Detours	Impr Model Parameters	DefaultRoadspeedFC01	94	Used only if detour and roadway speeds are missing
Default road speed, FC 11	Detours	Impr Model Parameters	DefaultRoadspeedFC11	91	Used only if detour and roadway speeds are missing
Default road speed, FC 12	Detours	Impr Model Parameters	DefaultRoadspeedFC12	83	Used only if detour and roadway speeds are missing
Default road speed, FC 14	Detours	Impr Model Parameters	DefaultRoadspeedFC14	83	Used only if detour and roadway speeds are missing
Default road speed, FC 16	Detours	Impr Model Parameters	DefaultRoadspeedFC16	48	Used only if detour and roadway speeds are missing
Default road speed, FC 17	Detours	Impr Model Parameters	DefaultRoadspeedFC17	48	Used only if detour and roadway speeds are missing
Default road speed, FC 19	Detours	Impr Model Parameters	DefaultRoadspeedFC19	32	Used only if detour and roadway speeds are missing
Default road speed, FC 2	Detours	Impr Model Parameters	DefaultRoadspeedFC02	87.8	Used only if detour and roadway speeds are missing
Default road speed, FC 6	Detours	Impr Model Parameters	DefaultRoadspeedFC06	80	Used only if detour and roadway speeds are missing
Default road speed, FC 7	Detours	Impr Model Parameters	DefaultRoadspeedFC07	80	Used only if detour and roadway speeds are missing
Default road speed, FC 8	Detours	Impr Model Parameters	DefaultRoadspeedFC08	40	Used only if detour and roadway speeds are missing
Default road speed, FC 9	Detours	Impr Model Parameters	DefaultRoadspeedFC09	40	Used only if detour and roadway speeds are missing
Default truck percent	Detours	Impr Model Parameters	DefaultTruckPct	5	Used only if truck fraction is missing
Detour speed factor	Detours	Impr Model Parameters	DetspeedFactor	0.8	Used only if detour speed missing
Height detours default	Raising	Impr Model Parameters	ClrDetoursDefault	0	
Height detours point A (X)	Raising	Impr Model Parameters	ClrDetoursThreshA	0	
Height detours point A (Y)	Raising	Impr Model Parameters	ClrDetoursFracA	0	
Height detours point B (X)	Raising	Impr Model Parameters	ClrDetoursThreshB	3.96	
Height detours point B (Y)	Raising	Impr Model Parameters	ClrDetoursFracB	10.81	
Height detours point C (X)	Raising	Impr Model Parameters	ClrDetoursThreshC	4.11	
Height detours point C (Y)	Raising	Impr Model Parameters	ClrDetoursFracC	0.18	
Height detours point D (X)	Raising	Impr Model Parameters	ClrDetoursThreshD	4.27	
Height detours point D (Y)	Raising	Impr Model Parameters	ClrDetoursFracD	0.05	
Height detours point E (X)	Raising	Impr Model Parameters	ClrDetoursThreshE	4.42	
Height detours point E (Y)	Raising	Impr Model Parameters	ClrDetoursFracE	0.027	
Height eligibility point A	Replacement	Impr Model Parameters	MinDualTTST	2.3	
Height eligibility point B (X)	Replacement	Impr Model Parameters	DualTTSTxA	18	
Height eligibility point B (Y)	Replacement	Impr Model Parameters	DualTTSTyA	64.32	
Height eligibility point C (X)	Replacement	Impr Model Parameters	DualTTSTxB	41	
Height eligibility point C (Y)	Replacement	Impr Model Parameters	DualTTSTyB	83.57	
Weight detour point A	Strengthening	Impr Model Parameters	StrDetoursMinThresh	2.3	
Weight detours point B (X)	Strengthening	Impr Model Parameters	StrDetoursCornerX	18	
Weight detours point B (Y)	Strengthening	Impr Model Parameters	StrDetoursCornerY	50.425	
Weight detours point C	Strengthening	Impr Model Parameters	StrDetoursMaxThresh	41	
Default traffic growth period	Traffic	Impr Model Parameters	DefaultADTchange	20	Used only if adtyear, adtfuture or adtfutyear missing
Weight given to user cost	User cost	Cost matrix	userweight	100	Default was the same for all functional classes
Cost per accident	Widening	Cost matrix	acccost	14247	Default was the same for all functional classes
High appr alignment rating	Widening	Impr Model Parameters	GAccRiskB	9	
Low appr alignment rating	Widening	Impr Model Parameters	GAccRiskA	2	
Regression constant	Widening	Impr Model Parameters	AccRiscCoeff	200	
Regression constant	Widening	Impr Model Parameters	GAccRiskC	6.5	
Short bridge threshold	Widening	Impr Model Parameters	MaxWidenLength	60	
Approach width factor	Widening	Impr Model Parameters	WidthDefFactor	0.9	
Design lane width	Widening	Policy matrix	dslanewid	3.7	Default was the same for all functional classes
Design shoulder width	Widening	Policy matrix	dsshldwid	2.4 or 4.9	Default was 4.9 for interstates, 2.4 otherwise

Policy, cost, budget, and improvement parameter data sets were all set to Default.
The extent of the scenario database was set to No Restriction on every dimension.
The Program Start Year was set to 1999.
The Planning Horizon was set to 1 year.
Replace Criterion was set to 999%.
Use Current Functional Needs and Only Optimal Projects were checked.
Minimum Project Cost was set to 0.
Deferment Years was set to 0.
Improvements Only was selected.

All of the default settings for level of service standards were used, as were all default configuration options except those described above. The budget constraint was set to $1 billion.

A total of 941 bridges were found to have functional needs in this simulation run. Among these 941 bridges, there were 7 with missing approach alignment ratings, one with a missing operating rating, two with missing adtfutyear, and 118 with missing adtyear. Since the software has procedures to accommodate all of these missing values, it was decided to keep all 941 bridges for further analysis. The 941 bridges represent a good cross-section of the inventory, with all functional classes of the original inventory well represented.

3.3. Verification of User Cost Calculations

In order to verify the documentation and the researchers' understanding of the model, an Excel spreadsheet was created to perform the calculations as documented for each of the 941 bridges found to have functional needs. This methodology is similar to the software testing methodology now under development in NCHRP Project 12-50 (unpublished). The spreadsheet included all Pontis data items that contribute to the user cost model, from the bridge, inspection event, and roadway tables. Joined to this data set was the funcneed table resulting from the simulation run described above, providing the types of improvements and the calculated benefits for each bridge.

A preliminary analysis of the data set verified that Pontis recognizes widening and strengthening needs only for roadways on a bridge, and recognizes raising needs only for roadways under a bridge. As a result, the data set was reduced to eliminate all rows which did not show this correspondence between the roadway.on_under column and the funcneed.fkey column. This had the effect of removing redundant rows resulting from the joining of the roadway and funcneed tables. After reducing the data set in this way, a total of 950 rows were left. Each row included the full set of data required for calculating user costs, plus the resulting benefit as calculated by Pontis.

The spreadsheet was then expanded by adding columns for all intermediate and final results of the user cost model, as documented in section 2.0 above. Model parameters from the Cost Matrix, Policy Matrix, and Improvement Model Parameters table were added on a second worksheet. The results of these calculations were compared with the Pontis results, and found to differ in only 5 cases. These cases appeared to be software bugs triggered by unusual data values, so they were removed from the data set. This resulted in a total of 945 cases on 938 bridges used in further analysis.

Although the Florida database was unusually free of missing values and obvious errors, a small number of suspicious data values were found. These were brought to the attention of FDOT, but no attempt was made to correct them for the analysis.

3.4. Sensitivity to Bridge and Roadway Data

The Florida database provides a good distribution of widening needs among functional classes, but raising needs are relatively uncommon and occur mainly on local roads. Only three bridges in the data set have strengthening needs. (See Figure 4.) Because of these facts, the sensitivity analysis placed an emphasis on widening needs, and thus the accident cost model.

One important aspect of sensitivity analysis is the effect of possible data errors on the model predictions. This kind of analysis is performed on observed data items describing the bridges in the database.

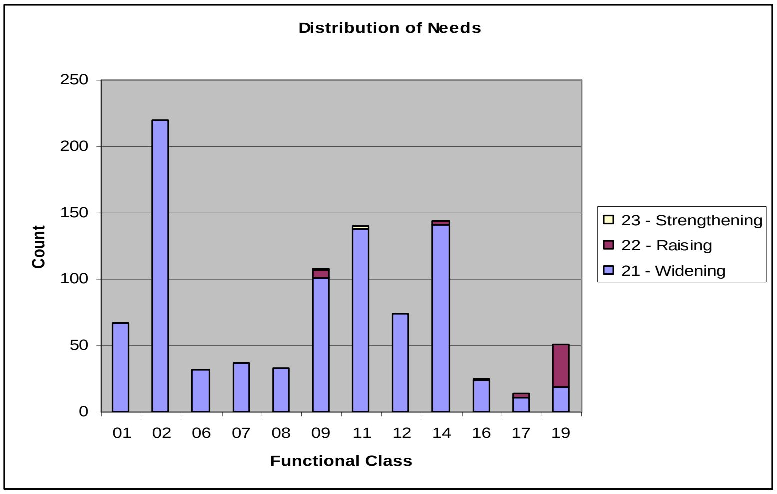


Figure 4. Distribution of need types

In many cases, the sensitivity of a data item can be determined by inspection of the model equations. For example, all user costs are directly proportional to traffic volume, as evidenced in equation (1). For raising and strengthening, user costs are directly proportional to the truck percent (equation 9 and 10) and detour distance (equation 12). A few input data, though, have non-linear relationships and therefore deserve special attention.

Approach alignment ratings in the Florida database are heavily skewed toward the high end of the scale, with most bridges having a rating of 8. Only 7 bridges have ratings below 5. This makes overall user costs relatively insensitive to errors in the rating. On average, a 1-point change either way in approach alignment rating changes total user costs by 4 percent in the Florida database. If all bridges in the data set had a rating of 2, the total user cost would increase by 21 percent.

Bridge roadway width is the second major factor considered in the benefit of widening. The distribution of widths in the Florida database is probably not unusual among the states, with most roadways in the 8-12 meter range. On average, the simulated widening in Pontis increased the roadway width by about 5 meters. The accident risk model is extremely sensitive to changes in the roadway width. An increase in roadwidth of 1 meter reduced user costs by an average of 92 percent, while a decrease of 1 meter increased user costs by a whopping 846 percent. The reason for this tremendous effect is the exponential form of the accident risk model in equation (4) above. The large exponent makes the model very sensitive to even very small changes.

Bridge length, approach road width, and number of lanes all affect the improved roadway width, which in turn affects user costs through the same exponent as in equation (5). Their effect on improved accident risk is therefore amplified in the same way as roadway width. However, because the improved accident risk is extremely small compared to the unimproved accident risk (by a factor averaging about 4,500), these variables have only a very small effect on project benefits.

For raising needs, the primary factor considered is vertical clearance for roadways under bridges. The data set for this is rather small: 8 bridges are under threshold A in the raising step function under equation (9); 5 under threshold B, 31 under threshold C, and 1 under threshold D. Out of these 45 bridges, 21 are within 2cm of a threshold, so there is significant exposure to the sensitivity of the threshold values. On average, an increase of 2 cm. in vertical clearance reduced the raising benefit by 65 percent, while a decrease of 2 cm. increased benefits by only 1 percent. The lack of symmetry is largely an artifact of the small sample size. However, the high sensitivity exhibited in the first case is because of a large discontinuity in the step function at point B. Only one bridge crossed the threshold (moving from 3.96 meters to 3.98), but its user cost increased by a factor of 60. Such discontinuities are a common problem with step functions and are probably unavoidable with this form of model.

Strengthening needs also have a very small data set in Florida. All three bridges fall between points B and C in the piecewise linear function contributing to equation (10). Operating ratings of deteriorated bridges are known with less certainty than clearances, so a larger variation was investigated. An increase of 5 tons in operating rating on these three bridges decreased user costs by 30 percent, while a decrease of 5 tons increased user cost by 35 percent. The piecewise linear function used in equation (10) has discontinuities that are far less severe than a step function. The effect on user cost is therefore much smoother.

3.5. Sensitivity to Model Parameters

Using the spreadsheet model, the sensitivity analysis was conducted by making incremental changes, one parameter at a time, from the default parameter values given in the lower part of Table 1. Increments were made in both directions (negative and positive) for each parameter. The ranges of those increments were determined in order to include in the analysis the values of each parameter found in the literature. More than 27 such analyses were prepared. The following sections describe the most interesting results.

3.6. Benefit of Widening

It is somewhat academic to investigate the sensitivity of the accident risk regression constants and specification constants, because there is no alternative source for this information other than to estimate a new accident risk model. The previous section noted that the model in equation (4) is extremely sensitive to roadway width, because of the exponent in the model. Table 2 shows that the model is also very sensitive to the value of the exponent. This is again another reason to avoid this functional form in an accident risk model.

Exponent	User cost ($millions)
1	218,876,908
2	15,534,179
3	1,287,323
4	143,208
5	19,007
6	2,715
6.5	1,039
7	399
8	60
9	9
10	1

Table 2. Sensitivity of the accident risk exponent

Design standards for lane width and shoulder width affect widening benefits by determining the accident risk of the improved roadway. This accident risk is determined by equation (5), which is basically the same as equation (4) and has the same problem with the exponent. It might therefore be expected that the model is quite sensitive to these parameters. In fact, the effect is extremely small. Reducing the design lane width from 3.7 meters (about 12 feet) to 3.3 meters (less than 11 feet) reduces benefits by only 0.01 percent.

The main reason for this is that the benefit is determined by subtracting the accident risk after improvement from the accident risk before improvement. Since the model is exceedingly sensitive to road width, the accident risk after improvement is much smaller than the accident risk before, by a factor averaging about 4,500. This implies that the improvement virtually eliminates excess accident risk, which is reasonable enough for the purposes of the model. The sensitivity analysis showed that the other factors affecting improved roadway with, such as the short bridge threshold and the approach width factor, also have small effects on the results.

3.7. Benefit of Raising

As equation (9) indicates, the benefit of raising depends on a step function describing the heights of trucks in the traffic stream. It is difficult to use a step function effectively in this application. Referring to Figure 1 above, two-thirds of Florida's clearance-impaired bridges occur in the ranges described by thresholds D and E, so it would be desirable to have more detail in that range. However, the effect on truck traffic is much greater in ranges B and C, so it would be desirable to have more detail there, too. When the software allows only 5 steps, it is impossible to provide enough detail to satisfy both needs. Every step is therefore a big one in terms of its effect on the user cost calculation.

The use of a step function does not necessarily make the raising model inaccurate, but it does make it imprecise. This is more detrimental at the project level than it is at the network level. If suitable data can be found, the model can be significantly improved merely by changing its functional form to piecewise linear or curvilinear.

3.8. Benefit of Strengthening

Equation (10) shows that the model for strengthening is similar to that for raising, except that a piecewise linear function is used to describe the weights of trucks in the traffic stream. Sensitivity analysis with the Florida data is not very meaningful here, because there are only three data points. A new quantification of the strengthening model might be of interest to other states, which typically have a much higher number of posted bridges than Florida. The functional form of the model is well-behaved, so there is no strong reason to change it at this time.

3.9. Detour cost

Detour unit costs per hour and per kilometer affect both raising and strengthening costs. In the Florida data set, 34 percent of the detour cost is vehicle operating cost, and 66 percent is travel time cost. Since the two cost factors are added together, the model is naturally about twice as sensitive to travel time cost as it is to vehicle operating cost, as indicated in Figure 5. However, since the cost of travel time is known with more certainty than the cost of vehicle fuel and maintenance, the effect of uncertainty might be about the same for the two factors.

Both the raising and strengthening models require the percentage of the traffic stream occupied by trucks. If this value is zero or missing, the model substitutes a default truck percent. Since this affects nearly half of the raising and strengthening projects in the Florida database, it is significant. User cost is directly proportional to it.

The model for travel time cost requires an estimate of the speed on the detour route. Florida does not have this information for any of its bridges, so the default speeds are used. The average detour speed derived from the default models for the Florida database is 32 kph.

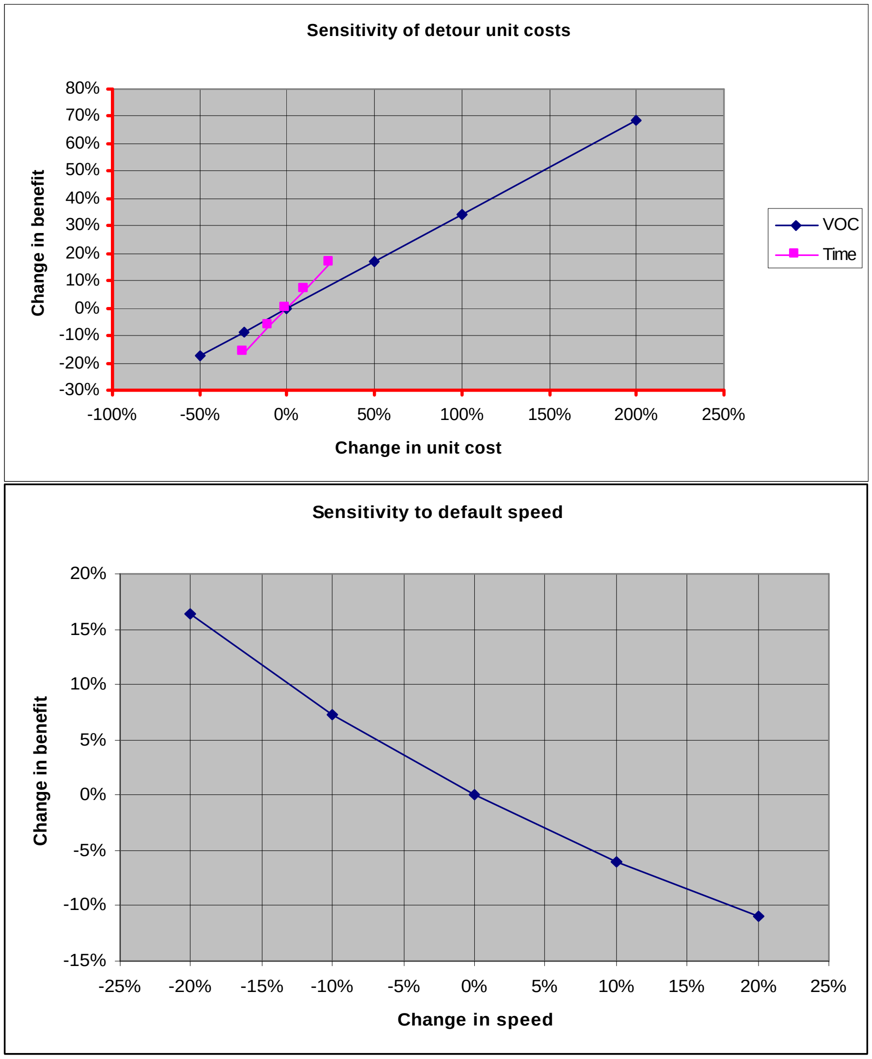


Figure 5. Sensitivity of detour unit costs and speed

4.0 Literature review and questionnaire

The literature review was conducted by searching the University of Florida library, TRIS, the Internet, and the personal library of Paul Thompson. More than 70 relevant papers and reports were found, most of them from outside the field of bridge management. The bibliography of each paper was consulted to locate secondary sources of information whenever possible.

A questionnaire was sent to all 50 states to inquire about any user cost research that they may have conducted or may have underway. As expected, none of the states has any recent work in this field beyond what was found in the literature.

4.1. Accidents

Most bridge management systems currently in operation use an accident model developed by North Carolina in the 1980s (Johnston et al, 1994). This model predicts accident risk based on bridge characteristics, and then applies an average accident cost in order to develop a user cost.

One alternative approach worth mentioning is the approach taken by Ontario in its new BMS, under development (Thompson, et.al., 1999). Ontario does not have usable accident data that can be related to bridge sites, and was not comfortable with the North Carolina model. It therefore elected to try a much simpler approach. The province over the years has systematically maintained reduced speed postings on all bridges having substandard geometrics. These speeds are determined on a site-specific basis from engineering considerations, and are regarded as reasonable safe speeds for each location. Working under the assumption that the posted safe speed is comparable, from a safety standpoint, to the general highway speed on the roadway approaching the bridge, the increased travel time resulting from the posting is regarded as a proxy for the safety-related user cost. This delay is calculated and used in the same way as vehicle operating cost.

4.2. Cost per accident

Among all the technical issues to be determined in the development of a user cost model, the most difficult is the economic penalty to be placed on the risk of death, injury, or property damage resulting from accidents. For the purposes of Pontis, it is necessary to find an acceptable value of C_a that causes functional improvement decision-making to become consistent with the public's non-quantitative expectation of safety.

The literature on traffic safety provides two different perspectives on the economic consequences of accidents, which have come to be known as the human capital approach and the willingness to pay approach. The human capital approach attempts to estimate the direct and indirect costs paid by society as a direct result of the specific accidents which have occurred. These costs include medical care, insurance and legal expenses, employer costs, lost productivity, property damage, and travel delay. In contrast, the willingness-to-pay approach estimates the amount of money the public would be willing to pay to avoid accidents. Implicitly, this cost includes intangibles such as pain and suffering, loss of enjoyment of life, inconvenience, and the premium associated with risk aversion. For bridge management, where the decision topic is the expenditure of public funds to prevent accidents, the willingness-to-pay approach would seem most suitable. For example, the Occupational Safety and Health Administration and the Office of Management and Budget use this approach for regulatory justification (Kragh et al, 1986).

Pontis does not distinguish among the types of accidents, so the costs of fatal, injury, and property damage accidents must be averaged together. There is evidence (Brinkman and Mak, 1986, citing Virginia and Kentucky data in Hilton, 1973, and Agent, 1975) that accidents related to narrow bridges are twice as likely to be fatal, compared to typical highway accidents. This is due to the finding that single-vehicle accidents have more than twice the percentage of fatal and incapacitating injuries as multi-vehicle accidents. Thus, the average accident cost should be weighted accordingly. No evidence has been found that other accident risk factors, such as alcohol and speed, affect bridge accidents differently from non-bridge highway accidents. However, icing may be related to higher accident risk on curved alignments in states with frequent freeze-thaw cycles.

Blincoe (1994) conducted an extensive analysis of highway accident costs and found the average costs shown in Table 3, under the human capital and willingness-to-pay approaches (all amounts in 1994 $000):

Table 3. Average costs per injury or damaged vehicle, 1994

Accident severity	Human capital approach	Willingness-to-pay approach
6 - Fatal	832	2855
5 - Critical injury	706	2509
4 - Severe injury	230	1194
3 - Serious injury	104	472
2 - Moderate injury	35	134
1 - Minor injury	7.2	11
0 - Non-injury	1.1	not given
Property damage only	1.7	not given

The willingness-to-pay figures were taken from Miller (1991) and updated to 1994 by Blincoe. These costs are given per injured person, for injury and fatal accidents, and per damaged vehicle, for property damage-only accidents. This is sometimes referred to as a cost per *incident*, as in Kragh, Miller, and Reinert (1986). It is necessary that either the accident cost or the accident risk be adjusted to reflect the number of injured people and damaged vehicles in each *accident*. It could be hypothesized that the number of injured people and damaged vehicles per accident would be smaller for bridge-related accidents than for other kinds of highway accidents, because in bridge-related accidents, the second object in the collision is often the bridge, rather than another vehicle. However, the literature contained no evidence to support this hypothesis.

Categories in the table shown above are based on the Maximum Abbreviated Injury Scale (MAIS), developed by the American Association for Automotive Medicine. As of 1986, it was more common for states to use the traditional A-B-C scale, which distinguishes the following categories:

F – Fatal
A – Incapacitating injury
B – Non-incapacitating injury
C – Possible injury
PDO – Property damage only

This is the classification scheme that was used by North Carolina in developing its models, and is also used in Florida. Useful complete definitions of these two classification schemes can be found in Kragh, Miller, and Reinert (1986). This paper also presents some 1986 costs per incident and per accident for the A-B-C scale. Abed-Al-Rahim and Johnston (1993) provide comparable figures for 1988-1990, including a reproducible methodology for generating these unit costs from published sources. Since the traditional A scale includes injuries (without an exact overlap) from MAIS levels 3, 4, 5, and 6, the MAIS scale provides better resolution for the more severe accidents. This is important when bridges tend to be associated with a disproportionate share of the more severe accidents. As indicated in Blincoe (1994), the user cost per incident for MAIS 5 injuries has been found to be almost as high as for fatalities.

Pontis has a default value of $14,247 per accident, which is based on Caltrans data for 1990. It is consistent with North Carolina data if the human capital approach is used. According to correspondence from Caltrans (Johnson, 1997), this figure has increased to $17,900 as of 1995. Pontis allows the accident cost to vary by functional class, district, on-system vs. off-system, and NHS vs. non-NHS. Caltrans accident cost data can distinguish rural, urban, and suburban roadways, so they use different values for urban and rural functional classes. The urban cost is $12,600 and the rural cost is $37,600 per accident. The methodology used at Caltrans does not account for the higher severity of bridge-related accidents.

If data from historical sources or from the literature are used to develop a unit accident cost for Florida, the cost should be updated to 1999 dollars. This is not strictly a matter of applying an inflation factor. As Blincoe (1994) noted, between 1990 and 1994 the 16 percent increase in estimated accident costs was partly offset by a decrease due to increased safety of motor vehicles and roadways. This left a net 8.1 percent increase in the unit cost per accident.

4.3. Accident Risk

Pontis is structured to use the North Carolina modeling framework, without flexibility to change the functional form of the model. Since the model is specific to the North Carolina BMS, there is no alternative source of parameters for the risk model. The following factors would affect any future development of a new accident risk model:

- Blincoe (1994) found that in 1994, roughly half of all property-damage-only accidents, and more than 20 percent of all non-fatal injuries, are not reported to police.
- It is quite difficult to determine, from most police records, whether each accident is related to a bridge, especially if the bridge was not directly a part of the collision. In the absence of better information, Brinkman and Mak (1986) recommend using any accidents within 500 feet of the bridge. It is possible to use a more sophisticated criterion than 500 feet, if speed and/or sight distance are known. In general, this distance should be based on the range within which driver behavior is affected.
- The use of the accident risk model in Pontis is to compare the accident risk of a deficient bridge with that of a non-deficient bridge. It is possible, but not required, to assume that a non-deficient bridge has the same accident risk as highway sections away from bridges.
- Accident risk varies by functional class, speed, and other factors. The risk estimates may have to be adjusted for differences between the analyzed sample and the statewide bridge inventory in general.
- Because of improvements in vehicle and roadway design, traffic enforcement, and other factors, there is evidence (Blincoe, 1994) that accident risk may be declining over time. Models based on older crash data must therefore be adjusted to account for the lower risk.

North Carolina provides a useful example for the process of estimating an accident risk formula, in Abed-Al-Rahim and Johnston (1993). The North Carolina models are based on a much smaller data set than Mak and Calcote, since they used only 5 counties with a total of 2,895 bridge-related accidents. Some of the conclusions of the effort were found to be counter-intuitive, perhaps due to the sample size or the difficulty of matching accident records with the correct bridges. However, the general methodology is sound.

Mak and Calcote (1983) found that the most severe bridge-related accidents in their database involved collisions with bridge parapet ends. The accident severity was far lower on bridges having modern end treatments. This and other research in the 70s and 80s led to improved design standards for guardrails, and efforts to retrofit older bridges. This can be expected to greatly reduce the severity of crashes. This would be an important factor to consider if updating older accident data for use in Pontis, and it could also significantly affect the transferability of models from one state to another.

If a new Florida accident risk model were developed to predict the risk of each MAIS or A-B-C severity level separately, this would be an important consideration. Pontis uses the user cost models to evaluate widening, raising, and replacement, but not for evaluating less expensive rail retrofit projects. When bridges are considered for functional improvement because of high accident severity experience, it is reasonable to ask first whether the problem could be reduced to tolerable levels by improvements to approach guardrails. Using the same logic, it is reasonable in principle to consider downgrading the severity of historical accident records if deficient guardrail end treatments were involved. A somewhat more practical approach would be to try using the end treatment adequacy as a possible explanatory variable in the risk model, if the data are reliable enough. Then this factor can be removed (by assuming that the retrofit is done even if no other functional improvement takes place) when evaluating the user cost implications of future functional improvements.

Using the evidence presented in Brinkman and Mak (1986), it is likely that the accident risk in Florida is sensitive to the number of lanes, direction of traffic, functional classification, speed, approach roadway width, and traffic volume. The model used in Pontis is not sensitive to any of these variables.

4.4. Vehicle Operating Cost

Four major sources of information on vehicle Operating Costs (VOC) were found. These sources are the Indiana BMS model (Son and Sinha, 1996), the North Carolina BMS model (Abed-Al-Rahim and Johnston, 1993), American Trucking Association (ATA, 1998) and the Highway Economic Requirements System (HERS) user cost technical report (HERS, 1996). A comparison of the results is shown in Table 4.

Table 4. Vehicle operating costs from several sources

Vehicle type	Indiana *$/km*	North Carolina *$/km*	ATA *$/km*	HERS *$/hr*
Passenger car	.072	0.28		0.71
Bus	.204			
Single-unit truck (all)	.173			
Single-unit truck (4-tire)				0.89
Single-unit truck (6-tire)				2.62
Single-unit truck (3-4 axle)				8.46
Tractor-trailer (all)	.261	.80	.775	
Tractor-trailer (4-axle)				5.92
Tractor-trailer (5-axle)				6.07

The Indiana model uses 1995 Indiana DOT weigh-in-motion (WIM) data, combining twelve-vehicle classifications into four: passenger car, bus, single-unit truck and tractor-trailer truck. A vehicle operating cost is developed for each vehicle type, based on research by the Texas Transportation Institute (TTI 1983), and the World Bank field tests (Zaniewski et al. 1982).

The North Carolina model assigns VOC for only two vehicle types: vehicles up to 3 tons including passenger cars and trucks; and vehicles over 3 tons. These were assumed to be the same as the Federal IRS tax allowance for the business use of a passenger car, plus operator costs from a North Carolina study. For tractor-trailer configurations, the source used was the US Department of Agriculture, which regularly compiles cost data for long distance hauls of fruit and vegetables.

HERS computes vehicle operating cost on an hourly basis as the average annual vehicle cost divided by annual usage. Annual vehicle cost includes fuel, oil, tires, maintenance and repair, and mileage-related depreciation. It does not include taxes. For autos in commercial motor pools and four-tire trucks, annual vehicle cost is based on a five-year life, with a 15 percent salvage value at the end, with initial cost from the Motor Vehicle Manufacturers Association. Annual usage is assumed to be 2000 hours. The use of personal autos for business purposes assumes mileage-based reimbursement, with no component for capital cost.

Six-tire trucks and four-axle combination trucks are assumed by HERS to be in service 2000 hours per year. Data from the 1982 Truck Inventory and Use Survey indicate five-axle combinations travel an average of 61,500 miles per year, while four axle combinations average 37,700 miles per year. Based on (Orange, 1988), trucks are assumed to travel an average of 41.4 miles per driver hour. Because three- and four axle single-unit trucks include many dump trucks that have down time between jobs, especially during cold periods of the winter, they are assumed to be in use only 1600 hours per year.

Of the four best sources found, the HERS model appears to be the most recent (1988) and most reliable. Note in the table above that HERS vehicle operating costs are expressed per hour and not per km, as in the other models. When converted to $/km, the HERS unit costs are considerably lower than the other studies.

4.5. Travel Time Cost

Two main sources of information were located about travel time cost: the Indiana BMS model (Son and Sinha, 1996) and HERS (HERS, 1996). These results are compared in Table 5.

Table 5. Travel time costs from two sources

Vehicle type	Indiana *$/hr*	HERS *$/hr*
Passenger car	9.75	11.12
Bus	10.64	
Single-unit truck (all)	14.96	
Single-unit truck (4-tire)		12.59
Single-unit truck (6-tire)		17.80
Single-unit truck (3-4 axle)		14.88
Tractor trailer (all)	22.53	20.02

Indiana evaluates the travel time cost using a study derived from the Texas Transportation Institute (TTI) in 1983. The HERS data in the table are from 1988. The HERS report also provides data for 1993 and advice on how the unit costs can be updated for other years.

To calculate the travel time costs, HERS includes labor, fringe benefits, inventory, and spoilage costs. (HERS also considers vehicle operating costs, as discussed in the previous section, and non-business use of autos and small trucks. These are excluded from the above table since they do not affect the Pontis travel time models.) No adjustment is made for taxes. Wage rates were obtained from the US Bureau of Labor Statistics. Fringe benefit rates for small vehicles were assumed to be the same as the national average, 19.73 percent according to the Statistical Abstract of the United States: 1989. For larger trucks, the fringe benefit rate was derived from a Teamster’s Union contract. Labor and fringe benefit costs are adjusted to account for vehicle occupancy. Most of the published sources for the HERS data have since been updated.

HERS includes an adjustment of 50 cents per hour for inventory and spoilage costs, for tractor-trailers. This adjustment recognizes the costs associated with merchandise carried by a truck when it is delayed. The assumptions behind this part of the model are rather complex. No adjustment is made for smaller trucks, whose contents are assumed to be less time-critical.

The HERS report includes a comparison of its hourly total truck cost (including vehicle operating cost) with two other published sources. This is reproduced in Table 6.

Table 6. Comparison of truck costs among sources

Study	5-Axle tractor-trailers	All medium and heavy trucks
HERS	26.09	23.99
Buffington & McFarland	24.04	21.74
Kamerud	29.24	24.56

5.0 Development of a new accident risk model

The sensitivity analysis showed that the accident risk model was unduly sensitive to roadway width and, of all the components of the Pontis user cost model, was least likely to fit 1999 Florida conditions. Moreover, there was no source in the literature for a better model. Because of the importance of this model to the Pontis analysis in Florida, and the existence of some excellent data resources within FDOT, it was decided to attempt to develop an improved Pontis user cost model for bridge widening.

5.1. Data preparation

The estimation data set was prepared by merging FDOT's Pontis data with highway crash data maintained by the Florida Department of Highway Safety and Motor Vehicles (HSMV, 1999). The year 1996 was chosen as the analysis year to ensure that all required data would be available for the same year. HSMV maintains crash statistics based on police reports, for most roads in the state.

Matching crashes to bridges. When the Pontis database was established in 1997-98, it relied on inventory data already maintained in FDOT's Roadway Characteristics Inventory (RCI). The RCI contains the same bridges as Pontis, using the same Bridge IDs, and also uses the same linear referencing system (County, Section, Subsection, Milepost) as the HSMV database. This made it relatively straightforward to develop an automated process to merge the two data sets. Using the RCI data it was possible to precisely locate the beginning and end of each bridge along the roadway. Following the recommendation made by (Brinkman and Mak, 1986) and also followed by (Johnston et al, 1994), all accidents from the HSMV database that were located within 500 feet of the beginning or end of a bridge were attributed to that bridge.

HSMV data are quite extensive for each accident, including not only the location and time of the crash, but also various items of data about drivers, vehicles, weather, injuries, and other circumstances. Very little data are provided about bridges, however. Along with location and identification data, the matching program selected certain items (such as number of lanes and ADT) that could be cross-checked with Pontis data to detect any unexpected problems with the matching process. No such problems were found. When occasional inconsistencies in such data were noted between the HSMV database and the Pontis database, the latter was taken as authoritative.

Injuries in the crash database are coded according to the traditional A-B-C system expressed in a numeric form, defined as follows:

1 – No injury
2 – Possible injury
3 – Non-incapacitating injury
4 – Incapacitating injury
5 – Fatal injury (within 90 days)

An estimate of vehicle and non-vehicle property damage is also recorded. HSMV follows up on crash reports after 90 days to determine the final count of fatalities and to update the property damage estimate, if available.

The initial matching process characterized the injuries in each accident according to the worst injury sustained, and a dollar value of property damage. Later in the study it was found that the most reliable available accident cost data in the literature were expressed as a cost per injury, rather than a cost per accident. This distinction is important, because each bridge-related accident in the Florida data set involves, on average, 2.09 vehicles, each vehicle carrying 1.43 persons. The HSMV database does include a listing of each individual (driver, passenger, or pedestrian) and his/her injury level in each accident. Since the matching process included a unique accident identifier for each crash, it was decided later in the study to request the detailed injury list and merge this with the estimation data set, to develop a count of injuries by severity level. This made it possible to determine the average user cost per accident.

Out of 11,332 accidents in the matched data set, 6,235 matched more than one bridge. More than 98 percent of these cases involved two or more parallel bridges, which share the same (or nearly the same) linear referencing information. Most of the remaining cases are bridges in series that are less than 1000 feet apart. Since the functional characteristics of the nearby bridges tend to be identical, it was assumed that each bridge was equally likely to be associated with the accident. The accident counts, injuries, and costs were therefore divided equally among them. As will be evident in the preliminary data analysis, this action has a substantial effect on the statistical properties of the data set by allowing for fractional accident counts and by reducing the number of bridges having no accidents associated with them.

Although the matching process was able to match roadways either on or under each bridge, it was decided to use only data for roadways crossing over bridges. This is consistent with the Pontis assumptions for widening, since widening usually does not affect the characteristics of roadways under bridges. Pontis is able to account for the user benefits of improving the roadway under a bridge when it is replaced, but there were doubts about the completeness of roadway-under data in the FDOT Pontis database.

Eliminating questionable bridges. A large number of bridges in the Pontis database have no corresponding accidents in the crash database. Usually, this is because no accidents occurred on the bridge during 1996. However, sometimes this could be because the bridge is outside the coverage of the crash database. For this reason, certain bridges and their associated accidents, if any, were removed from the data set, as follows:

- All bridges coded in Pontis with district 8 belong to the Florida Turnpike Authority. Accidents on the Florida Turnpike are not included in the crash database, so all district 8 bridges were deleted.
- The Pontis database includes only a few local, county, or Federally-owned bridges, and the coverage of these bridges in the crash database is uncertain. Therefore, all bridges with NBI Item 22 (owner) codes of 2, 4, 11, or 60 or above, were deleted. (Some of the remaining codes did not occur in the database.)
- Only bridges that carry highway traffic should be considered in the analysis. Therefore, NBI Item 42A (service type on bridge) was checked to ensure that no bridge coded 2, 3, 9, 0, or missing was included. Also, NBI Item 102 was checked to ensure that no bridge coded 0 or missing was included. The database was also checked to ensure that all bridges had non-zero and non-missing traffic volume.

In general, an earlier analysis of the FDOT Pontis database found that it was unusually free of missing values and obvious data errors. A few additional checks were performed to eliminate suspicious data values that might bias the model. These include the following:

- All bridges coded with more than 20 lanes
- All bridges with roadway width or approach roadway width less than 3 meters
- All bridges where approach roadway width divided by roadway width was greater than 2.0
- All bridges where roadway width divided by the number of lanes was less than 9 feet

These rules removed fewer than 30 bridges from the data set. A few additional bridges had missing values for deck condition rating or approach alignment rating. In both cases, these bridges were found to have accident experience consistent with ratings of 9, and so the missing value codes were changed to 10 for convenient grouping with the 9s.

One more potential source of error is the fact that the Pontis data are up-to-date as of the time of the research (1998), while the crash data are from 1996. During the intervening two years, a number of bridges were widened or replaced. This could make the Pontis data inconsistent with the crash results. To ensure than no such bridges would bias the analysis, all bridges with year-built or year-rehabilitated of 1996 or later were deleted. There were 96 such bridges.

After the completion of the data preparation phase, the estimation data set contained 4,505 bridges with 10,012 crashes.

5.2. Preliminary analysis

Over the past 16 years, Florida has made significant progress in reducing the crash and death rates on its roads. The overall crash rate on all roads (including state and local) has declined from 484 crashes per 100 million vehicle miles in 1981, to 186 in 1996 (HSMV, 1997). Similarly, the death rate has declined from 4.10 per 100 million vehicle miles, to 2.16 in the same period.

Bridges on the Florida state highway network have a lower rate of roadway width deficiencies than the national bridge inventory. In the estimation data set, only 17 percent of the bridges were rated as failing the default Pontis level-of-service standards. Table 7 places the roadway width deficiencies, and their safety implications, into a statewide perspective. In this table, the injury categories are as defined in section 5.1. Vehicle miles are calculated to include the 500-foot zones before and after each bridge.

Table 7. Florida crashes, injuries, and property damage per 100 million vehicle-miles (1996)

	Crashes	Fatal	Injury 4	Injury 3	Injury 2	Damage ($000)	Vehicle-mi. (millions)
Roads statewide	186.19	2.16	24.58	60.31	102.80	NR	129,637
State highway bridges	91.26	0.85	11.05	26.40	56.37	424	10,971
Narrowest 10%	170.61	1.42	18.10	43.38	103.59	738	1,337
Narrowest 100 bridges	224.03	1.29	26.18	57.51	126.18	901	233

NR = not reported

State highways in general are constructed to higher standards than local roads, and thus exhibit lower crash and injury rates. State highway bridges also conform to this pattern. Nevertheless, the remaining deficiencies have a significant effect on public safety. For reasons described below, the term “narrowness” in this report is defined as the number of lanes (NBI Item 28A) divided by bridge roadway width (NBI Item 51). Table 7 indicates that the narrowest bridges have more than twice the crash rate of the Florida state highway bridge inventory as a whole.

Another interesting conclusion from the data behind Table 7 is that the crashes on narrow bridge sites are not more severe than crashes on the state bridge inventory as a whole, nor are they more severe than those on statewide roads as a whole. This contradicts the conclusions noted in the North Carolina study (Abed-Al-Rahim and Johnston, 1993), upon which the existing Pontis models are based. The North Carolina study reports 0.019 fatalities per bridge-related accident for 1984-1989, as compared to 0.009 in Florida. Similarly, an earlier study (Hilton, 1973) concluded that crashes related to narrow bridge sites were twice as severe as non-bridge crashes. The Hilton study reasoned that the greater severity was due to a high incidence of single-vehicle accidents on bridge sites, which tend to be more severe than multi-vehicle crashes. In the Florida data set, only 19 percent of the accidents on bridge sites were single-vehicle crashes. The lack of a significant difference in crash severity may reflect improvements in recent years in the safety of bridge guardrails, as well as vehicle safety improvements such as air bags. Also, the North Carolina data set included locally-owned bridges, which the Florida set does not.

Later in the present study, an effort was made to develop a separate predictive model of crash severity (as distinct from crash risk) related to bridge characteristics. This effort proved entirely inconclusive. No significant relationship was found between crash severity and any physical characteristic of the bridge in the Pontis database, including such variables as roadway width, approach alignment, and even safety features (NBI item 36). In fact, the only variable in the data set that had a significant relationship to severity was truck percentage.

Overall then, the preliminary analysis indicates that narrow bridge sites are at least twice as likely to have accidents as non-narrow sites, but these accidents are not significantly likely to be more severe. For development of a user cost model, this bodes well for the likelihood of developing a statistically significant model of accident risk, if not severity.

5.3. Exploratory data analysis

Accident rates and crash severity at bridge sites can be influenced by a large number of factors, including facility characteristics, driver behavior (such as alcohol, speed, seat belt use, and experience), and vehicle characteristics (such as air bags and vehicle construction). A complete model of bridge-related accidents would need to consider all of these factors in order to have a high degree of explanatory power. However, the purpose of the present analysis is only to evaluate the potential user cost savings of certain facility improvements, so the effect of driver and vehicle characteristics, even if it could be determined, would not necessarily add to the usefulness of the model for a BMS.

In the literature, a number of researchers (Abed-Al-Rahim and Johnston, 1993; Brinkman and Mak, 1986; Agent, 1975; Hilton, 1973) have investigated the causal factors of bridge-related accidents. All have generally focused on facility characteristics, assuming that driver and vehicle characteristics are randomly distributed. No evidence was found in the literature to contradict this view. It is important to point out, however, that this assumption omits some of the most important predictive factors for accidents. It must be expected, therefore, that conventional statistical measurements of model explanatory power, such as r-squared, will be quite low. More important objectives for this research include:

- All independent variables must be reliably available in Pontis.
- The model specification must be explainable based on an intuitive or theoretical understanding of accident causation, and must be consistent with available literature on this subject.
- The independent variables must be relevant to policy and project decisions analyzed in the BMS.
- The resulting model must stand up to a sensitivity analysis such as was performed in Section 3.0.
- If possible, the model should be transferable to other states. This means that it should avoid Florida-specific explanatory variables unless they have high significance or strong interactions with the policy variables of the model. Limiting the model to NBI data items would maximize the transferability to states that are not users of Pontis.

The limited availability of data on facility characteristics in Pontis further reduces expectations for r-squared and makes the other objectives listed above more important. For example, the available data sets currently lack speed, congestion, sight distance, pavement skid measurements, characteristics of nearby intersections, and climate information. In some cases there may be proxy data items that can indirectly represent some of this missing information.

Although the regression analysis documented in this report attempts to maximize r-squared, the existence of important random variables outside the model means that any effort to optimize the model formulation with elaborate data transformations or large numbers of independent variables, is likely to be misleading. There is a risk of over-fitting, where the analysis gains slightly better regression statistics by developing a correlation with the random component of the data. This type of improvement seldom holds up when the model is validated with a new set of data. To avoid over-fitting, it is important to use only variables that have a clear intuitive or theoretical relationship to the dependent variable.

5.4. Dependent variable

Accident risk in the literature is usually expressed in the form of accidents per 100 million vehicle miles. In a database of measured crash data, this measure is calculated by dividing the number of accidents by the product of average daily traffic and roadway segment length. A predictive model of accident risk measured in this way therefore assumes that the number of accidents is a direct multiple of traffic volume and segment length.

This assumption could be problematic for bridges. The nature of bridge accidents is that the driver is suddenly presented with a new set of fixed obstacles to avoid, or a lack of escape routes to be used in order to avoid a collision with another vehicle. Although it is clear that there should be some relationship between traffic volume, segment length, and accident count, this might not be a direct multiplicative relationship. For example, the North Carolina model predicts accidents as a multiple of traffic volume but not of length. It would also be possible to develop a model to predict accident counts directly. It is not obvious in advance which of these three approaches best fits the phenomenon now being modeled, so the research investigated all of them.

A traffic accident is inherently a very unlikely event. In the Florida data set, the passage of one vehicle over one state-owned bridge happens over 107 million times per day, yet only 27 crashes occur each day on those bridges. In 1996, 45 percent of the bridges in the estimation data set had zero accidents identified with them. This does not mean that the future accident risk on these bridges is zero; it means that these bridges were lucky enough to avoid accidents in this one year. This presents some statistical complications, because clearly the dependent variable in the model is not normally distributed.

Figure 6 shows that the distribution of accident counts is heavily skewed toward zero, with zero the most numerous value at 2018 occurrences. Ideally for a regression analysis, it is desirable for the dependent variable to be normally distributed. Figure 7 shows that this ideal is more closely realized if the dependent variable is transformed by using the log function; in this case, the graph shows the log of annual accidents per million ADT. However, this begs the question of what to do about the 2018 zero values, whose log is undefined.

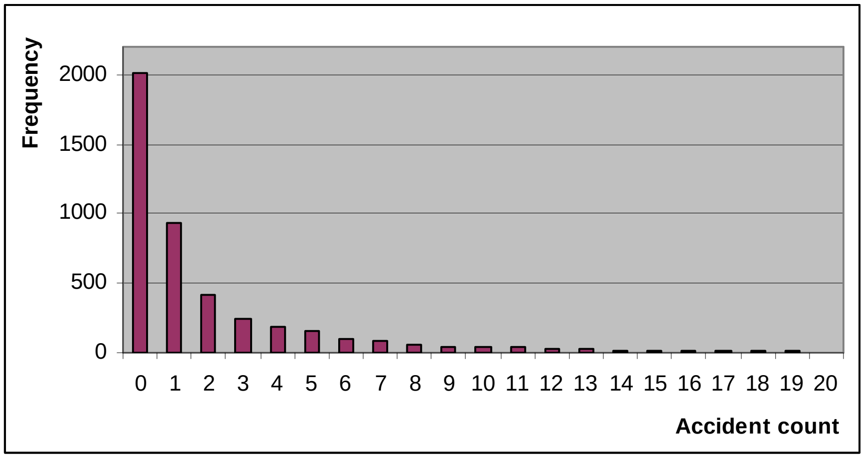


Figure 6. Frequency distribution of accident counts

Figure 7 makes it evident that the zero values are actually an approximation of most of the left-hand tail of the distribution. It is likely that a longer time-series of data, perhaps 10 years' worth, would reveal fractional annual accident rates on most of these bridges, possibly forming the traditional bell-shaped curve of a normal distribution. However, this cannot be proven from the available data.

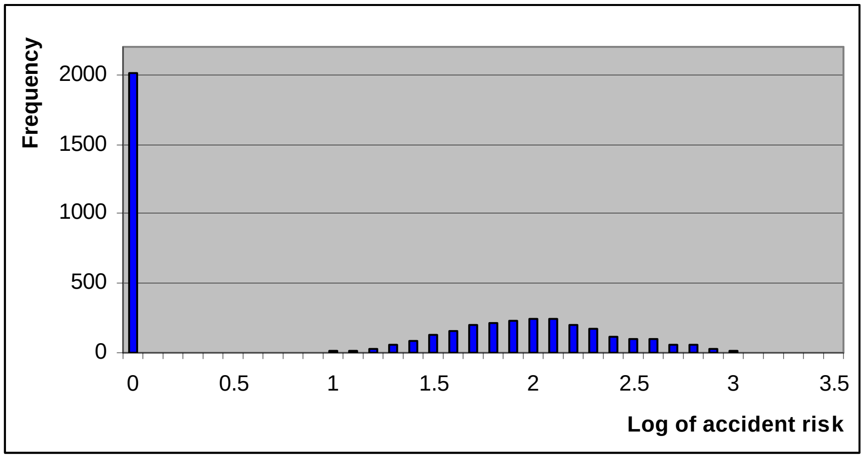


Figure 7. Frequency distribution of the log of accident risk

One approach that partially addresses this problem is the assumption, made in the data preparation step, that parallel bridges share the same accident risk. In every case where an accident was associated with more than one bridge according to the linear referencing system, the accident was divided evenly between them. This resulted in fractional accident counts on many bridges that might otherwise show zero accidents.

Another possible approach that was not investigated in the study is to form groups of bridges that are similar according to the independent variables in the model. For example, the 4,505-bridge data set could be collapsed into 901 groups each having 5 bridges. The regression analysis would then be performed on a data set having a sample size of 901. This would reduce, but not eliminate, the probability of zero accidents. This approach was not chosen largely because, with many major explanatory variables (e.g. driver and vehicle characteristics) absent, it was far from guaranteed that the added complexity would actually produce a better model. With the smaller sample size, many of the hypothesis tests described below would not have enough statistical significance.

The simpler approach that was chosen was to assume that the zero values are actually approximations of small non-zero values. The dependent variable was chosen to satisfy the requirement that residuals (the difference between the actual value and the value that would be predicted by the model) would be as small as possible for values near zero, so that their potential to bias the model would be minimized. Accident count is the variable that best satisfies this criterion.

5.5. Independent variables

Prior to the estimation of a regression model, it is important to develop a theoretical or intuitive basis for the model, to explain how the possible explanatory variables might affect the outcome. The elements of this intuitive model can then be tested, using graphics, correlation analysis, or hypothesis testing, to see if they have any statistical significance and to learn more about the relationship. This process, overall, is called exploratory data analysis. Over the course of the analysis, it became clear that hypothesis testing would be the most informative approach for this data set. Attempts at graphical analysis of the data, using scatter plots and other more elaborate tools, were generally inconclusive because no one variable could explain very much of the variability in the data set. Correlation analysis was occasionally useful, but sometimes suffered because of interactions among explanatory variables, and because of non-normality.

Hypothesis testing focused on dividing the data set into two samples according to each of the candidate explanatory variables, and determining whether the two samples differed in their accident rates in a statistically significant way that agreed with the intuitive model of accident causation. Accident rates were expressed in annual accidents per million ADT, under the assumption that accident counts would be approximately proportional to traffic volume. In the discussion that follows, the units of accident risk are abbreviated as "aamdv," which stands for annual accidents per million daily vehicles. The average accident risk in the estimation data set is 81 aamdv.

In statistical analysis, the t-test is most commonly used to determine the statistical significance of a comparison between two means. Unfortunately, the t-test is strongly biased if the distribution of values being averaged is far from normal, as is true for accident risk in this data set. Fortunately, an alternative method called the Wilcoxon rank-sum test provides similar information without the bias. In the exploratory analysis described here, the Wilcoxon rank-sum test was always more conservative than the t-test, and was always relied upon for conclusions about statistical significance.

The following sections describe the intuitive model of accident causation investigated in the study, with the results of the related statistical analyses.

Narrowness. It was anticipated (and later proven) that the strongest variable in the model, relevant to bridge management, would be the narrowness of the bridge roadway. This variable should describe the reduced availability of escape paths on a narrow bridge, the increased likelihood of side-swiping the guardrail, and the possibility of bouncing off the guardrail into another vehicle. Narrowness should be expressed as some sort of relationship between roadway width and number of lanes. Variations might include using traffic volume instead of number of lanes, and adding the curb/sidewalk width to the roadway width. Bridge length might interact with this variable, since a longer bridge increases the time in which the loss of escape paths exists.

A correlation analysis between narrowness and accident risk was performed, using each potential definition of narrowness. The highest correlation (19.5%) came from dividing the number of lanes (NBI 28A) by the roadway width (NBI 51). In particular, this definition was stronger than its reciprocal (-17.4%). This makes intuitive sense, because it means that changes in roadway width for a narrow roadway make more of a difference than changes in a roadway that is already wide. The values of narrowness according to this definition range from 0.06 to 0.36 in the estimation data set. The wide range is usually because of shoulder widths or merging of lanes.

This correlation is small, but statistically significant. If the data set is divided into two roughly equal-sized samples according to roadway width divided by number of lanes, the dividing point is approximately 18 feet per lane. The bridges above this value have an average annual accident risk of 53 aamdv; those below this value (the narrower half of the inventory) have an average accident risk of 109 aamdv. The difference between these two means is significant at a confidence level much greater than 99%. This confirms that narrow bridges are twice as likely to have accidents as wide bridges.

Table 8 shows the distribution of bridges into narrowness categories, and the accident risk in each category. This categorization was prepared for possible use as an explanatory variable in the model, but in the end it did not improve the model. Nevertheless, it does demonstrate the clear strength of narrowness as an explanatory variable.

Table 8. Summary of bridges categorized by narrowness

	>=7.5m	6.75-7.5	6-6.75	5.25-6.0	4.5-5.25	3.75-4.5	<3.75m	Total
Number of bridges	222	105	1500	652	833	929	264	4505
Average accident risk	36	41	54	67	101	117	130	81

Note: The columns in this table are ranges of roadway width divided by number of lanes, in meters.

Funnel. Another possible accident cause is the "funnel" zone where the roadway narrows at the entrance to the bridge. This was represented as the approach road width (NBI 32) divided by the bridge roadway width (NBI 51), and ranges from 0.28 to 1.96 in the estimation data set.

The correlation analysis indicates that funnel has a 0.39 correlation coefficient with narrowness, but only a 0.064 correlation with accident risk. Bridges whose approaches were wider than their bridge roadways (52% of the data set), had an average accident risk of 87 aamdv. Bridges whose approaches were narrower had an average accident risk of 74 aamdv. This difference is statistically significant with more than 99% confidence.

Approach alignment. This data item (NBI 72) is treated as a categorical variable in the model. Table 9 shows that a systematic relationship does appear to exist between approach alignment and accident risk. However, because of the small sample sizes in some of the categories, the differences in accident risk are not always statistically significant.

Table 9. Summary of bridges categorized by approach alignment rating

	2	3	4	5	6	7	8	9	10	Total
Number of bridges	2	7	15	63	148	457	2594	1198	21	4505
Average accident risk	293	307	192	118	120	103	75	77	41	81

Note: An approach alignment rating of 10 in this table indicates that the rating was not provided

To achieve a statistically significant predictor, the approach alignment categories were grouped together. It was found that dividing the inventory into two groups, where the first has a rating less than or equal to 6, provided a difference in mean accident risk that was significant at the 95% confidence level. According to the NBI definition, an approach alignment rating of 6 is the highest rating where safe travel speeds are affected. The average risk in the first category was 109 aamdv, and in the second was 74 aamdv.

Deck condition. It was theorized that a deck in poor condition might increase the risk due to other functional deficiencies, or might cause a higher accident risk in its own right. A clear relationship was found in the data, though again it was necessary to group categories together to achieve statistical significance. According to the NBI definition, a deck rating of 6 is the first where minor deterioration is evident. The estimation data set has 323 bridges with deck ratings less than or equal to 6, with an average accident risk of 128 aamdv. The remaining 4182 bridges have an average accident risk of 76 aamdv. The difference in accident risk is significant at the 99% confidence level.

Functional classification. As shown in Table 10, functional classification clearly has an effect on accident risk. However, many of the classes did not have sample sizes large enough for statistically valid conclusions to be drawn. All of the model formulations tested in the regression analysis therefore combined functional classes together in various ways. It was considered likely that there could be strong interactions between functional class and any or all of the other explanatory variables, so this possibility was tested thoroughly.

Table 10. Summary of bridges categorized by functional class

	1	2	6	7	8	9	11	12	14	16	17	19	Total
No. of bridges	647	766	314	82	57	93	883	553	751	285	33	41	4505
Av. Acc. risk	49	62	83	46	1	16	71	77	144	137	40	6	81

Bridge length. The length of a bridge could have a direct or indirect effect on accident risk. When analyzing a segment of ordinary road, it is usually assumed that accident counts are proportional to the length of road considered. The relationship to bridges, however, was not as strong. The correlation between accident risk and bridge length (NBI 49) of only 19.5 percent is similar to that of the narrowness variable. About half of the bridges in the data set had lengths greater than 60 meters, with an average accident risk of 90 aamdv. The remaining shorter bridges had an average risk of 72 aamdv. This difference is significant at the 99% confidence level.

Number of lanes. A roadway with multiple lanes in the same direction presents a more complex environment to the driver than a single-lane road, and therefore might be related to a higher accident rate. This possibility was confirmed with a correlation between number of lanes (NBI 28A) and accident risk of 15.7%.

Traffic direction. Bridges with two-way traffic (according to NBI 102) also present a more complex environment to the driver and may contribute to a higher accident risk. The 1,658 bridges with two-way traffic in the data set had a risk value of 101 aamdv, compared to the remaining bridges with a risk value of 69 aamdv. This is significant at the 99% level. The possibility that this effect might depend on median type (NBI 33) was investigated in the model estimation process. Median type was not significant by itself.

Flared structure. When NBI item 35 is true, it indicates the possibility of merging lanes that may contribute to accident risk. On the 229 bridges where this occurred in the data set, the average accident risk was 129 aamdv, compared to 78 aamdv for the remaining bridges. This is significant at the 99% level.

Pedestrians allowed. Bridges with service type (NBI 42A) set to 5 allow both pedestrians and vehicular traffic. This could increase the possibility of pedestrian collisions or pedestrian-caused distractions. On the 508 bridges where this situation occurred, the average accident risk was 165 aamdv, compared to 70 aamdv on the remaining bridges. This is significant at the 99% level.

Traffic volume. Pontis, like the NBI, codes traffic counts along with the year the counts are taken, and separately codes a predicted count for a future year. Section 2.1 describes the method of estimating traffic volume for any intermediate year.

ADT has two potential effects on accident counts: a direct effect due to the number of vehicles exposed to risk, and an indirect effect when a driver might be distracted by the behavior of other drivers. The direct effect is clearly significant: accident count has a 55.4% correlation with ADT. The indirect effect, quantified by the correlation between accident risk and ADT, is a relatively weak 0.067%. Bridges with traffic volume above the median had accident risk of 98 aamdv, while those below the median volume had an average accident risk of 64 aamdv. This is still significant at the 99% level.

Truck percent. It was theorized that high truck traffic might be associated with higher accident risk because of the reduced maneuverability of large trucks. This was not corroborated by the analysis, however. The correlation between truck percent and accident risk was –0.054, which is very small and also the wrong sign.

Ramp. Ramps could have an adverse effect on accident risk, especially in colder climates. However, since ramps are usually one-way roads, the effect could be positive. There was no opportunity to test either hypothesis in this study, however, because none of the bridges had level of service (NBI 5C) coded as 7.

Weather. Weather is usually cited as a contributing factor in accident causation. In Florida, where the weather is quite uniform and warm, there are no extremes of snow and ice that might have a noticeable effect on accidents. This would undoubtedly be different in other states. This would affect the transferability of the model only if weather interacts with the policy variables of the model.

District. Used as a proxy for weather or local maintenance and operational policies, district could have some effect on the model. This was tested in the exploratory analysis and in the regression model, but only very small, marginally significant differences were found. These did not interact with the policy variables of the model, so it was decided to omit district as an explanatory variable.

Speed. Although it could be a significant explanatory variable and could interact strongly with other causal factors, it turned out to be impossible to include speed in the model. Pontis has a speed column in the database, but this is currently not populated. (FDOT is in the process of populating it in its regular cycle of inspections, however.) The crash database also has a speed field, and it also is not populated in the majority of cases. Functional class could be considered a proxy for speed, but the statistical evidence did not support this. Higher-type functional classes tended to have lower accident rates, probably because they are built to higher standards and lack at-grade intersections.

5.6. Final model

After the completion of exploratory data analysis, a regression analysis was performed in order to develop the final predictive model. Three types of regression analysis were performed:

- Ordinary least-squares, which uses all the data points and results in a model that is linear in all of the explanatory variables. Each explanatory variable may be a linear or non-linear function of zero, one or more columns from the bridge database.
- Least trimmed squares, which is the same as ordinary least squares but eliminates a given number of outliers from the calculation of residuals.
- Tree regression, where the data are successively divided into “bins” by ranges of the explanatory variables in a way that minimizes the variability within bins. This type of model handles any non-linear type of problem structure, returning a decision tree for selecting a value of the dependent variable.

Because of low expectations for model explanatory power, it was decided not to attempt a non-linear regression analysis other than the tree model. The non-linear aspects of such a model could be misleading because of the absence of important explanatory variables. However, if a few more explanatory variables were available, especially speed and alcohol use, the problem structure would lend itself especially to a multinomial logit or probit model, to predict the likelihood of crashes in each injury class.

The final model selected was a relatively simple linear regression model to predict accident counts (expressed in thousands for convenient display of the coefficients). Similar model specifications using least trimmed squares and tree regression did not produce significantly better models. However, eleven outliers were detected and removed at the end of the analysis to develop the final model coefficients. Tables 11, 12, and 13 describe the model.

Table 11. Data used in the final model

Name	Description	Pontis table	NBI Item	Range in data
funcclass	Functional class of roadway on bridge	roadway	26	1 to 19
lanes	Number of lanes on bridge	roadway	28A	1 to 12
length	Length of the bridge	bridge	49	1.8 to 10887.5 m.
appralign	Approach alignment rating	inspevnt	72	2-9 (missing=10)
roadwidth	Width of roadway on the bridge	roadway	51	3-58 meters
adttotal	Most recent average daily traffic count	roadway	29	1-295,000
adtyear	Year of most recent traffic count	roadway	30	1988-1998
adtfuture	Future traffic forecast	roadway	114	0-538,375
adtfutyear	Year of forecast	roadway	115	2015-2020
dkrating	Condition rating of deck	inspevnt	58	1-9 (missing=10)

Table 12. Intermediate variables

Name	Formula	Range in data set
UrbanArterial	funcclass=14 or 16	true or false
AlignLE6	appralign<=6	true or false
Narrowness	lanes/roadwidth	0.06-0.36
ADT	see Section 2.1	1 to 324,806
BadDeck	dkrating<=6	true or false

Table 13. Model statistics

For bridges where	Variable	Coefficient	Std. Error	t value
UrbanArterial=false	Constant	-377.3701	66.0689	-5.7118
UrbanArterial=true	Constant	886.0098	106.9613	8.2835
All bridges	lanes×length	0.7323	0.0455	16.1039
AlignLE6=false and BadDeck=false	Narrowness×ADT	0.3904	0.0087	44.9273
AlignLE6=true and BadDeck=false	Narrowness×ADT	0.5031	0.0194	25.8690
AlignLE6=false and BadDeck=true	Narrowness×ADT	0.4531	0.0257	17.6592
AlignLE6=true and BadDeck=true	Narrowness×ADT	0.7899	0.0556	14.2052

Sample size = 4,494; multiple R-squared = 0.5422

To apply this model for forecasting, first calculate the intermediate variables as in Table 12. ADT should be calculated for the program year being analyzed, using the method described in Section 2.1. In the first and third sections of Table 13, determine which coefficient applies to the bridge in question. For example, if a bridge has functional class 11, an approach alignment rating of 5, and a deck condition rating of 7, then choose the first coefficient for Constant, and the second one for Narrowness×ADT. All bridges use the same coefficient for lanes×length.

Next, in the second and third sections of table 13, multiply the variable by the coefficient, then add the results together along with the selected constant. Divide the results by 1000 to yield the predicted accident count. For the example in the preceding paragraph, a 4-lane bridge 100 meters long with narrowness of 0.2 and ADT of 10000 would be calculated as:

$$(-377.3701 + 0.7323\times4\times100 + 0.5031\times0.2\times10000) / 1000 = 0.922 \text{ accidents per year}$$

The range of predicted accident counts in the data set, using this model, is –0.371 to 30.324. The range of actual accident counts is 0 to 95.25. The average predicted accident count is 2.077, compared to actual values averaging 2.222. The average residual, or absolute value of the difference between actual and predicted, was 1.696. Thus, the model under-predicts accidents at the extremes of its range, but performs reasonably well in the middle of the range. This is consistent with a relatively conservative approach to the estimation of project benefits, so it is not necessarily an adverse characteristic of the model.

If this model is used in Pontis, the value of R_r for equation (3) in Section 2.2 is calculated simply by dividing the predicted accident count by ADT. The value of R_r' is calculated in the same way, except using predicted values of the explanatory variables following the improvement. For widening, only the narrowness and deck condition are changed. For replacement, approach alignment would also change. Replacement tends to change the number of lanes and length of the bridge, which could reduce the improvement benefit somewhat. However, if lanes and length are changed, this is normally for reasons beyond the scope of the Pontis analysis, so it would be justifiable to ignore this part of the change within Pontis.

Model realism and performance. In the estimation data set, 13 percent of the bridges had small negative accident predictions. All of these bridges had 0 or 1.0 as the actual accident count. This fact, which was common to all the model specifications tested, results from the model's attempt to approximate the large number of zero values for actual accident counts in the data set. Although a negative accident count may seem counter-intuitive, it does not harm the intended application of the model. When actually applied in Pontis or any other BMS, the model should be used to compare a substandard bridge with an improved bridge. The difference between the two predictions of accident counts should always have the correct sign, since the coefficients of Narrowness×ADT all have positive signs and behave in the expected way with respect to approach alignment and deck rating.

The R-squared goodness-of-fit test for this model was unexpectedly high, suggesting that the model explains 54% of the variation in the data. This is somewhat misleading, because the data set itself has less variation than the true behavior of the phenomenon being modeled, with the large number of zero values for accident counts. In general, all of the models predicting accident counts had R-squared values in the range from 0.45 to 0.58, reflecting the fact that this formulation was least biased by the zero accident counts. Models of accident risk per ADT or per vehicle mile had much lower R-squared values and showed more evidence of bias. As the final model itself indicates, accident risk has a strong, but not fully proportional, relationship to both ADT and bridge length.

All of the coefficients in the final model have high t-statistics, indicating that they are significant at confidence levels far higher than 99 percent. The regression procedure does not have a significance test analogous to the Wilcoxon rank-sum test suitable for non-normal data, so it was necessary to be very conservative in the interpretation of the t-statistics.

Stability. Because of the relative rarity of accidents in general, a special concern in the modeling process was its sensitivity to unusual data values. This sensitivity can be exhibited by instability of the modeling results on alternative data sets. To attempt to detect such instability, most of the model estimation process was conducted on a random 50% sample of the full 4,505-bridge data set. When a promising model formulation was completed, it was validated on the remaining half of the data set to see if this would yield consistent results. Only the final model was estimated on the full data set, to develop the final coefficients. Models that included a large number of explanatory variables almost always failed this stability test.

The solution to this problem was to reduce the number of explanatory variables to just the essentials. In particular, the following decisions were made:

- Certain variables that were not affected by bridge widening or replacement decisions were eliminated from the model, even if they were statistically significant. In particular, traffic direction, flared structure, and pedestrians allowed, all were significant in the model but contributed to instability.
- Categorical variables were reduced to true/false variables. This is especially noticeable with functional classification. Several ways to group functional classes were attempted, but in the end it was decided to break out only urban arterials, because their effect was especially significant and they did not cause instability. Similar concerns applied to approach alignment and deck condition, reinforcing the decisions about statistical significance that were made during the exploratory data analysis.

It is possible that larger sample sizes might reduce the stability problem and allow more variables to be included. However, for the purposes of a BMS, the added variables would not add any decision support power.

Interactions. It was suspected in the exploratory data analysis stage that there could be significant interactions among explanatory variables. An interaction is any situation where the effect of one variable changes depending on the value of another variable. The original Pontis model in equation (4) in Section 2.2 contains a significant interaction between roadway width and approach alignment, which was evident in the North Carolina research. The current research strongly supports the existence of this interaction, though the functional form of it is different from the one used in North Carolina. In addition to this major interaction, the following other ones were investigated:

- Deck condition was found to have a significant effect on accident counts when included as a separate variable. However, when expressed in an interaction with narrowness and approach alignment, the model was much stronger. The combined effect of bad geometrics and a bad deck is significantly greater than the separate effects of these deficiencies.
- Lanes and length. These variables performed well when included in separate terms of the model, but their performance was even better when combined. When accident risk is stated in terms of vehicle-

miles, there is an implicit assumption that accident counts are proportional to bridge length. The modeling process did not support this assumption. Bridge length did not perform well when combined with narrowness and alignment, but was still significant when combined with the number of lanes.

- Traffic volume. When accident risk is stated in terms of either ADT or vehicle miles, there is an implicit assumption that accident counts are proportional to the number of vehicles exposed to the risk. This was not fully supported by the model. ADT was significant when combined with narrowness, alignment, and deck condition, forming the most important term in the final model. But ADT significantly reduced the strength of the model when combined with lanes, length, and/or functional class.
- Funnel. The funnel variable was tested as an alternative to narrowness and in combination with it as either a separate variable or as an interaction. It did not perform well in any of these roles. Because of the moderate correlation between funnel and narrowness, both variables were weakened when the two were combined. When tested as alternatives, narrowness was much stronger than funnel. As a result, funnel did not survive into the final model.
- Median type. This was tested alone and in interactions with all the other variables in the model. It did not have a significant effect in any of these roles.
- Functional class and truck percent. These variables are correlated with each other, so they did not perform well together in the same model. When tested as alternatives, functional class was stronger. It was anticipated that functional class might interact with any or all of the other explanatory variables, but all such interactions caused instability or weakened the model.

Whenever an interaction occurs, it is still permissible to use the interacting variables separately in the same model. Sometimes this acts to correct an over-emphasis on the variable in the interaction, so often the lone variable has a counter-intuitive sign. Deck condition was an example where a correction variable improved the model slightly. This was eliminated from the final model, however, since its significance was marginal. All of the interacting variables were investigated in this way, but no others had enough effect to justify their inclusion in the final model.

6.0 Unit cost parameters

Pontis uses three unit user costs in its model: cost per accident, vehicle operating cost per kilometer, and travel time cost per hour. None of these were available from FDOT, so they were determined from the literature.

6.1. User cost per accident

Injury costs in the models developed for FDOT are based on the work of Blincoe (Blincoe, 1994), converted to the A-B-C injury system based on medical descriptions of injuries in Blincoe's original data set, and updated to 1996 dollars using the Consumer Price Index. Property damage estimates are already stated in 1996 dollars. Table 14 summarizes the Florida accident data and user costs. As discussed in Section 4.2, the willingness-to-pay approach is more commonly used in public investment decision making.

Table 14. Accident user costs and their application to Florida (1996)

Injury category	Willingness-to-pay	Human capital	Florida counts
Cost per injury			
1 – No injury	$ 0	$ 0	NA
2 – Possible injury	29,844	8,815	6184
3 – Non-incapacitating injury	45,927	12,289	2896
4 – Incapacitating injury	211,515	49,294	1212
5 – Fatal injury (within 90 days)	3,014,525	871,697	93
Property damage	NA	NA	$ 46,537,676
Cost per bridge-related accident	$ 89,972	$ 27,712	

NA = not applicable

These costs can be updated to later years using the consumer price index (CPI). In 1999 dollars, the costs per accident are $94,291 and $29,042 respectively under the two approaches. However, growth is likely to be slower than the CPI because of continued improvement in safety features that reduce the severity of accidents.

An analysis was conducted to determine whether the accident cost should vary by functional class, as is allowed in Pontis, or by any other variable. For each bridge, an average user cost per accident was calculated according to the willingness-to-pay approach, and this was used as the dependent variable in exploratory data analysis and regression analysis as described in the preceding sections. The results of this analysis were inconclusive. The best regression model provided an R-squared value of only 0.12, with costs that varied little by functional class. Only truck percent was a significant predictor in any model.

As a result of this analysis, it is recommended that a single cost per accident, $94,291 using the willingness-to-pay approach in 1999, be used for all bridges in the BMS database.

Even though the new cost per accident is much higher than the Pontis default value (under the willingness-to-pay approach), the total user costs calculated by the new model are much lower, due to a lower estimated accident risk on the narrowest bridges. Total annual user benefits from the 945 functional improvement projects analyzed in the sensitivity analysis spreadsheet was reduced from $1,040 million under the old model to $84 million under the new model. The average user benefit of a widening project under the new model is now $93,541 per year. Assuming a conservative 3% real interest rate and a life of 30 years, the average life cycle benefit of a widening project is over $1.7 million, which is still much greater than the average cost of bridge widening. Thus, the new model provides more realistic user cost estimates without changing the fundamental justification for most widening projects.

Most of the user cost reduction occurred on a small number of bridges that exhibited large changes in roadway width. Since user cost now has a linear relationship to all explanatory variables, there is far less variability in project benefits among bridges.

Accident cost is still the most significant component of user cost in the Florida database, though its percentage of user costs has been reduced from 99.9 to 98.9. Under the new model, accident risk still tends to dominate project priorities, but the effect is not as strong as it was before. Traffic volume, functional class, bridge length, and number of lanes all have a stronger effect on priorities than under the old model, while the effect of roadway width has been reduced.

Deck condition now has a significant effect on priorities. For bridges with approach alignment ratings better than 6, deck condition ratings of 6 or lower tend to increase user benefits of widening by 15 percent. This effect is increased to 57 percent for bridges with approach alignment ratings of 6 or worse.

6.2. Vehicle operating cost per kilometer

The research uncovered a very good source of truck operating cost data in the Florida Trucking Association. Table 15 summarizes the data for 1992, the most recent available year. The total cost equates to 28 cents per kilometer, which is very consistent with the literature and only slightly more than the Pontis default of 25 cents.

Table 15. Non-labor tractor-trailer line-haul costs, 1992

		Cents per mile	Percent of total
Total fuel/oil & fuel taxes		17.31	38.0%
Fuel, oil & lubes	10.81		
Fuel taxes	6.51		
Equipment (depreciation/lease)		8.68	19.0%
Total maintenance		5.41	12.0%
Vehicle parts	3.66		
Outside maintenance	1.75		
Other operating costs		2.77	6.0%
Taxes/licenses, not fuel		2.76	6.0%
Insurance		2.71	6.0%
Tires & tubes		2.54	5.5%
Total miscellaneous expenses		3.28	7.2%
General supplies/expenses	1.58		
Communication & utilities	0.46		
Deprec-not tractor-trailer	0.33		
Use-other motor carriers	0.66		
Rents-bldg/office equip.	0.25		
Total non-labor costs		45.46	

Source: Florida Trucking Association

The US Bureau of Labor Statistics (BLS) maintains price indexes that can be used for updating these numbers, as shown in Table 16. Each column of the table is a BLS price index: the first is the Consumer Price Index, available from the BLS web site at http://stats.bls.gov/cpihome.htm. The remaining columns are relevant components of the Producer Price Index, available at http://stats.bls.gov/cpihome.htm under the link labeled, "Producer Price Index – Commodities." In the row labeled "Most recent," the CPI is given for February 1999, while the other indices are averages for 1998, the most recent data available.

Table 16. BLS price indices

Year	CPI	Fuel	Tires	Motor Veh	Parts	Totals
1992	140.3	68.1	98.4	129.9	113.1	
1993	144.5	63.9	98.3	134.2	113.8	
1994	148.2	61.7	97.8	139.1	114.3	
1995	152.4	63.7	99.0	140.3	116.0	
1996	156.9	72.8	95.4	141.5	116.2	
1997	160.5	71.9	93.6	139.7	115.4	
Most recent	164.5	53.3	92.2	137.6	114.6	
Percent increase, 1992 to present	17.25	-21.73	-6.30	5.93	1.33	
Weight	25.50	38.00	5.50	19.00	12.00	100.00
Weighted percent	4.40	-8.26	-0.35	1.13	0.16	-2.92

Source: US Bureau of Labor Statistics

An interesting fact apparent from this table is that the costs of fuel and tires have declined significantly since 1992. The row labeled "Weight" represents the percentage of total Vehicle Operating Costs assumed to vary with each index, according to the percentages given in Table 15. All costs other than fuel, tires, equipment, and maintenance are assumed to vary with the Consumer Price Index, which has by far the fastest growth rate of any of the indices given. Nonetheless, the total weighted index for vehicle operating costs has declined by nearly three percent since 1992. Adjusted for this index, the recommended value for unit vehicle operating cost for Florida's implementation of Pontis is 27 cents per kilometer.

6.3. Travel time cost per hour

The research uncovered two good alternative sources of travel time cost. The Florida Trucking Association reports travel time costs in cents per mile, as in Table 17.

Table 17. Tractor-trailer labor costs, 1993

		Cents per mile	Percent of total
Driver wages		47.90	64.0%
Support labor		9.42	12.5%
Salaries-officers/managers	2.79		
Vehicle repair wages	5.07		
Wages-not driver/repair	1.56		
Fringe benefits		17.65	23.5%
Total labor costs		74.97	

Source: Florida Trucking Association

The literature review also found good sources of travel time costs. The best of these appears to be the Highway Economic Requirements System (HERS, 1996), which recommends a 1993 cost of $23.22 per hour for tractor-trailers, including an allowance of 58 cents for inventory and spoilage costs. (HERS also includes vehicle capital costs in its hourly cost, but in the Florida data and in Pontis, vehicle capital costs are handled as depreciation or leasing costs as part of the vehicle operating cost figure instead.) If this figure, less the inventory/spoilage allowance, is divided by the Florida Trucking Association (FTA) cost per mile, the result implies an average speed of 30 miles per hour. This is not unreasonable for the older bridges where functional deficiencies tend to occur. It is safe to say, then, that the FTA data are reasonably consistent with the literature.

It is debatable whether labor costs should be ascribed to travel time or to travel distance. In most sectors of the economy, including short-haul trucking, drivers are paid by the hour. However, long-haul drivers increasingly are paid by the mile instead. In the long-term, this question would be the most important determinant of whether to use the FTA (per mile) data, or the HERS (per hour) data.

In the short-term, a more relevant consideration is the fact that the Pontis detour cost model requires an estimate of the detour speed in order to convert detour distance to time. FDOT currently does not have detour speed data for any of its bridges. On the other hand, Pontis can accept a cost per kilometer for travel time cost, as long as the detour speed is set to 1. Inspection of equation (12) in Section 2.6 makes it clear why this is so. The FTA labor cost translates to 46.59 cents per kilometer. The HERS inventory and spoilage cost adjustment adds 1.39 cents, for a total of 47.98 cents per kilometer.

Regardless of which approach is used, labor costs must be inflated to current-year dollars. This is appropriately done using the Consumer Price Index which, according to Table 16, has increased by 13.84 percent since 1993. In summary, then, there are two alternative approaches to labor costs:

1. Use the HERS estimate of cost per hour, which is $26.43 in 1999 dollars. In this case, speed data must be provided, either by data collection or by using the Pontis default speeds.
2. Use the FTA estimate of cost per mile, which when adjusted as described above is $0.55 per kilometer in 1999 dollars. In this case, the default speeds should all be set to 1.

7.0 Truck height and weight

Truck height and weight histograms were the only area where the study was unable to find satisfactory Florida-specific data. These were considered lower priority because of the small number of clearance and load capacity deficiencies on the Florida state highway system. However, they could become more important if Pontis is ever implemented for local roads.

7.1. Truck height

The FDOT Permits Office has provided data on over-height trucks based on special permit applications. These data are available only for heights of 14 feet or greater, as given in Table 18.

Table 18. Truck height distribution, 1998

Height	Single-trip permits	Blanket permits
14	16594	8459
15	1476	5
16	290	12
17	37	0
18	46	569
19	10	0
20	11	0
21	7	0
22	8	0
23	3	0
24	7	0
25	6	0
>25	13	0

Source: FDOT Permits Office

These data would not be directly usable in Pontis with the default level-of-service standards, because the default vertical clearance standard is 14 feet. Pontis is intended to analyze the benefits of improving functionally-deficient bridges, and it would be difficult to justify a claim that bridges with clearances greater than 14 feet are functionally deficient.

Based on these considerations, it must be concluded that truck height histograms specific to Florida are not available at this time. In addition, the literature review did not uncover any alternative sources of this information. For the near-term, therefore, it is recommended that the current Pontis defaults be used.

At some future time, truck height data can be collected by means of a brief, simple procedure implemented at weigh-in-motion sites. An observer with a surveyor’s transit can be positioned at a known location at each site. A graduated target is positioned in the field of view of the transit, on the opposite side of the travel lanes. As a truck approaches the site, the observer records the lane position of the truck, and reads a measurement of the top of the truck from the target. The actual truck height is then calculated based on the geometry of the installation.

If possible, the truck weight from the weigh-in-motion device should also be recorded. This would make it possible to estimate the number of trucks that might be detoured by both height and weight at the same bridge, to eliminate double-counting.

This type of experiment could be completed in just a few days, by carefully choosing dates, days of the week, and hours of the day in a manner that avoids bias. The experiment should be repeated at several points in the state to determine whether there is geographic variation. It may be useful to repeat the experiment on other functional classes of roads, even though weigh-in-motion sites may not be available there, to ensure an unbiased model applicable to those functional classes that are most likely to have vertical clearance deficiencies.

7.2. Truck weight

Raw data for truck weight is available from weigh-in-motion facilities located throughout Florida, chiefly on interstate highways. To develop Pontis truck weight histograms, it is important that the raw data contain all vehicles in the traffic stream, including those that do not exceed legal weight limits. This is because the Pontis models are intended to estimate the user cost of bridge postings, which generally fall below legal weight limits. It is likely that the distribution of vehicle weights on interstate highways differs from other types of roads, so adjustments may be necessary in order to expand the weigh-in-motion data to represent the full range of bridges.

One of the authors has studied weigh-in-motion data from the Florida facilities (Najafi et.al., 1997) and found that the data are not currently adequate to derive a histogram of legal-weight vehicles. No usable source was found in the literature, either. In the Florida database, there are only three bridges with strengthening needs. Therefore, the development of a truck weight model would be considered very low priority unless locally-owned bridges are added to the system.

8.0 Summary of recommendations

Table 19 summarizes the results of all phases of the study to indicate the recommended handling of all data items in the Pontis user cost model. All but one of these recommendations can be implemented immediately or in the normal course of bridge inspections. The one exception is the new accident risk model, which requires enhancements to Pontis as described in the 23 October 1998 enhancement request submitted to the AASHTO Pontis Task Force.

Table 19. Summary of Recommendations

Data item(s)	Findings	Recommendations
Policy matrix dimensions	The cost matrix uses district, functional class, ownership, and NHS status, while the policy matrix uses ADT class instead of district. These items are almost never missing.	Fill in missing data during inspections.
Recent and future ADT, and their years	These items are missing on only a small fraction of structures.	Quality control check when collecting and recording traffic volume data.
Default traffic growth period	Not used on any bridges.	Keep Pontis default of 20 years.
Roadway width	Missing in 12% of cases, but most are roadways under bridges.	This would be high priority for attention during inspections.
Approach alignment, deck rating, number of lanes, length, approach road width	Missing in rare cases.	Fill in missing data during inspections.
Short bridge threshold	671 of the 898 bridges identified for widening had lengths less than or equal to 60 meters.	Use the Pontis default of 60 meters.
Width deficiency factor, and design lane and shoulder widths	These are design standards that should differ from the Pontis default only if there is an FDOT policy on this.	Keep the Pontis default values.
Accident risk regression coefficients	The existing model is excessively sensitive, and would not yield usable results with any value of the coefficients.	Use the new accident risk model in Section 5.6.
Average cost per accident	No FDOT-specific data were found, but the literature search provided good information.	Use $94,291 based on the willingness-to-pay approach (Section 6.1).
Vertical clearance, operating rating, and detour distance	Missing in rare cases.	Fill in missing values during the normal inspection and load rating processes.
Truck percent	Rarely has missing value codes, but there are many zero values that may also represent missing data.	Quality control check when collecting and recording traffic volume data.
Detour speed and roadway speed	Missing from all bridges.	Collect roadway speed in normal inspections.
Default truck percent	A median value of 8% was found on the state highway system bridges.	Use the median 8% value.
Default road speeds and detour speed factor	Existing Pontis defaults are reasonable.	Keep the Pontis default values.
Truck height and weight histograms	No usable source was found in FDOT or in the literature.	Keep the Pontis default values for now. Possibly collect the data in a special study.
Replacement height eligibility histogram	This is used in an inconsistent manner in the Pontis models, but does not affect any bridges on the state highway system.	Set all values of this variable to 100, effectively removing it from the analysis.
Detour cost per kilometer	No FDOT-specific data were found, but the literature search provided good information.	Use 27 cents per km. according to the analysis in Section 6.2.
Detour cost per hour	No FDOT-specific data were found, but the literature search provided good information.	Use $26.43 per hour according to the analysis in Section 6.3, assuming speed data will be collected.

9.0 Additional modeling issues

Two additional modeling issues have been raised, which are not currently addressed in Pontis.

9.1. Work Zone User Costs

Pontis provides a place to enter a project-level work zone user cost, which is added to the denominator of the benefit/cost ratio when setting priorities. Florida currently has no data to calculate this value, and Pontis does not provide any support for it. Further investigation may uncover possible data sources for certain projects, but this investigation is beyond the scope of the current study.

It may be possible, in principle, to predict user costs of work zones, using queuing models to estimate the travel time and reliability impacts. So far this has not been done in a BMS, though an existing FHWA model, QUEWZ, could possibly be applied for this purpose. The biggest difficulty of a work zone user cost model is accounting for the availability of alternate routes and the level of congestion on those routes. Even the best GIS maps may lack information on alleys, dirt tracks, and private roads that could be used as detour routes. A large number of strategies are available to mitigate work zone user costs, including signage, demand management, public transportation, night/weekend work, and construction of temporary bridges. If all alternate routes are also congested, travelers may change their trip-making behavior to compensate. Clearly the issue is much larger than bridge management and is common to all major construction projects.

9.2. User Cost of Movable Bridge Openings

Florida is interested in developing a user cost model for movable bridge openings, to help justify replacement projects for its large inventory of movable bridges. Based on preliminary inquiries, it appears that suitable data on bridge opening frequency and duration may exist for many of these bridges. With this information, it is conceptually feasible to develop a user cost model that contributes to the benefits of bridge replacement.

Modifications to the Pontis software would be required in order to implement this model. This possibility is discussed in the 23 October 1998 enhancement request submitted to the Pontis Task Force.

10.0 Implementation report

The Implementation Report is mandated by the FDOT Research Center Program Manual to provide guidance and concrete steps to help the research results to be put into practice as broadly as possible. The following sections describe the implementation plan.

10.1. Technical summary

The purpose of this research has been to analyze the Pontis user cost model in the context of Florida DOT requirements, to locate data that can be used to customize the model for Florida purposes, and to develop a plan for any additional work necessary in order to make the user cost model operational within FDOT's implementation of Pontis.

All of these objectives have been met. The Final Report provides a complete listing of all data requirements of the model, with a description of the recommended approach to satisfy every requirement. In some cases the recommended data have been derived from FDOT sources, while in other cases, such as economic data, the recommendations have been derived from an exhaustive review of available literature.

In one very important area, the research objectives have been exceeded. Early tasks in the study identified the development of a new model of accident risk to be of highest priority for future work. With the approval of the FDOT Project Manager, a portion of the project resources was redirected to the statistical analysis of available highway safety data, to develop the required model. The results are reported earlier in this report.

From the literature review, it was determined that the most recent accident risk model that has actually been applied in bridge management systems is more than fifteen years old and has some notable deficiencies. The new model was developed with technology transfer as an objective, to make it suitable not only for FDOT, but also for any other agency that is implementing a bridge management system. Because of its clear advantages over previous models, it is likely that the new model will see broad application in future systems worldwide.

For the most part, the recommended data developed in this study can be implemented in FDOT's bridge management system simply by entering the recommended data values into appropriate places in Pontis. The major exception is the new accident risk model. In a memorandum dated October 23, 1998, FDOT submitted an enhancement request to the AASHTO Pontis Task Force, to provide the ability to use externally-calculated user benefits in the Pontis program simulation. To date, the Pontis Task Force has not responded to this request. Through FDOT's continuing involvement in the design of new features for Pontis, the Department should continue to pursue the enhancement request and insist that the required capability be provided in the next Pontis release.

10.2. Technology transfer plan

Preliminary results of the study under Task 2 were submitted to Cambridge Systematics, Inc. for posting in the Pontis Technical Notes in November, 1998. To date, this has not been posted. However, the same information was presented in a paper at the International Bridge Management Conference in Denver in April, 1999. The conference attendance included the key staff responsible for bridge management system implementation in a large number of states and foreign countries. Additional information on the study was sent to several state DOTs and universities that requested it.

A draft paper describing the entire study and emphasizing the new accident risk model, has been prepared for the year 2000 Annual Meeting of the Transportation Research Board, under the auspices of subcommittee A3C06(3), "Bridge Management Systems." An effort will be made to have the paper published in a future issue of Transportation Research Record.

Under subtask 5.2 of the contract, a Powerpoint presentation has been prepared for FDOT management. The same presentation will be given to the Pontis User Group meeting in Madison, Wisconsin, in September, 1999, and at the 2000 TRB Annual Meeting.

Upon FDOT acceptance of the final report, it will be distributed electronically to all agencies that responded to the Task 1 survey. Respondents to the survey were asked to provide e-mail addresses for that purpose. Updated addresses for many of the respondents were obtained in a subsequent survey for the Agency Cost Study.

10.3. Implementation test plan

The user cost model developed in this study is just one small part of FDOT's overall effort to implement the Pontis bridge management system. Pontis is intended to support improved bridge program decision-making by presenting objective information on the costs and benefits of policy and project decisions.

Many of the most difficult Pontis implementation steps, such as the establishment of a client-server database and the institution of a new bridge inspection process, have already been accomplished by FDOT. A completely populated database will be available late in the year 2000, at which time the system may begin to enter production usage for decision support. A companion study to develop agency cost models for Pontis is also scheduled to be complete by that time.

An important feature of a bridge management system is the ability to estimate the costs and benefits of alternative bridge program decisions. Using this capability, it is possible to measure the benefits of the system by comparing its recommended decisions with those that might have been pursued without the aid of the system. Since Pontis measures only the economic benefits of bridge projects, the system does not consider non-economic factors such as political mandates. The actual programs implemented with the help of Pontis might therefore vary from those that the system would recommend on purely economic grounds. The user cost model developed in this study is an important part of the system's ability to measure the economic benefits of bridge investments.

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