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# Effect of Slope and Headpond on Passage of American Shad and Blueback Herring through Simple Denil and Deepened Alaska Steeppass Fishways

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*Abstract.*—Passage and transit time of adult upstream-migrant American shad *Alosa sapidissima* and blueback herring *A. aestivalis* were investigated in standard Denil and Alaska steeppass fishways with variable slope and headpond under semicontrolled conditions. Percent of American shad passed per unit time (percent passage) increased with temperature, while time required to ascend from the fishway entrance to the exit (transit time) decreased with increasing temperature for both species. Increasing fishway slope decreased percent passage of American shad, regardless of fishway type. Higher fishway slope decreased percent passage of blueback herring in the steeppass fishway only. Low headpond enhanced percent passage of American shad in the Denil fishway, but decreased percent passage of American shad in the steeppass fishway. Headpond level had no effect on percent passage of blueback herring in either fishway. Because headpond level in the steeppass fishway affected percent passage of American shad but not the smaller blueback herring, the relatively small cross-sectional area of the steeppass fishway operated at low headpond may inhibit passage of larger species such as American shad. Transit time of American shad decreased with both increasing slope and high headpond, and American shad increased through-water swimming speed under these conditions. American shad appeared to regulate their swimming speed through Denil-type fishways below maximal values. Blueback herring ascended the fishways at speeds comparable to those of American shad. Shorter transit times were not associated with increased percent passage. Turbulence and air entrainment may influence percent passage of American shad more than longitudinal water velocity.

Although simple Denil and steeppass fishways were originally designed for upstream passage of adult salmonids (Denil 1909; Ziemer 1962), they are increasingly used for passage of nonsalmonid species (McLeod and Nemenyi 1940; Slatick 1975; Beach 1984; Katopodis et al. 1991; Clay 1995). The advantages of Denil-type fishways (Larinier 1992) are that they are relatively inexpensive to construct and maintain, can operate under a wide range of natural discharge (headpond) conditions, and are primarily suited to smaller streams and low head dams. These advantages have made Denil-type fishways an attractive option for providing passage for anadromous clupeids in coastal rivers. However, the performance of Denil-type fishways has rarely been evaluated with respect to passage of anadromous clupeids, and their efficiency in passing these species has been difficult to determine (Larinier and Travade 1992). Slatick (1975) observed that adult American shad *Alosa sapidissima* readily passed a model-A steeppass fishway at 24% (1:4.2) slope, but passage performance was dependent on fishway entrance and exit conditions. American shad were observed to ascend short (<15.2 m) steeppass fishways at slopes of 23.3% (1:4.3) to 28.7% (1:3.5) but were unable to ascend a steeppass fishway 20.1 m long at 28.7% slope (Slatick and Basham 1985).

Slope and headpond level (depth of water at the fishway exit) are two major design and operation characteristics of Denil-type fishways that markedly affect hydraulics (water velocity, turbulence and air entrainment) and presumably passage performance. Schwalme et al. (1985) noted no apparent differences in ascent of several species of nonsalmonid fishes between two operational simple Denil fishways at 10% (1:10) and 20% (1:5) slopes, but their field observations lacked extensive replication and experimental control. Tack and Fisher (1977) found little effect of slope (7.5–15%; 1:13.3–1:6.7) or headpond (fishway discharge of 0.53–1.07 $m^3/s$) on Arctic grayling *Thymallus arcticus* greater than 130 mm in total length (TL) passing an Alaska steeppass fishway 6.1 m in length, although fewer grayling less than 130 mm TL were able to pass at the highest slope.

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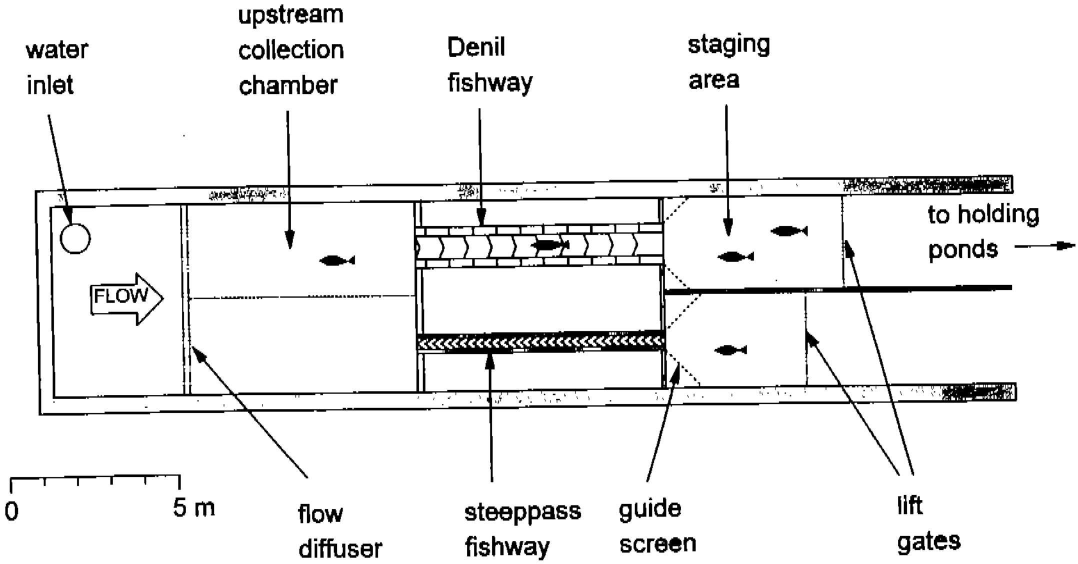


FIGURE 1.—Plan view of flume and installation of Denil and steeppass fishways. Dotted lines indicate screening; solid lines are solid walls or fishway structures.

Our objectives for this study were to determine the effect of slope and headpond on (1) percent passage (percent of an introduced group of fish that passed in 3 h), and (2) transit time (time required to ascend from the bottom of the fishway to the top) of adult migratory American shad and blueback herring *A. aestivalis*.

## Methods

*Fishway design and operation.*—Two variable-slope experimental fishways, a simple Denil and an Alaska steeppass (hereafter referred to as the steeppass), each 7.62 m long, were tested in the flume facility at the Conte Anadromous Fish Research Center (CAFRC), Turners Falls, Massachusetts (Figure 1). The steeppass fishway was a deepened model-A prefabricated aluminum structure similar to that developed by Ziemer (1962). The fishway was 56-cm wide overall (35.5 cm, clear width) and 102 cm deep (conventional model-A steeppass fishway depth is 68.6 cm). The baffles (12.7 cm wide) were placed 25.4 cm apart at 30° into the flow. The Denil fishway was constructed at CAFRC in the form of a simple Denil recommended by the Committee on Fish Passes (1942) with timber, steel, and plywood. Dimensions were 1.22 m wide (0.71 m, clear opening) × 1.22 m deep. The baffles were placed 76 cm apart and at 45° inclination to the bottom. Each fishway was supplied with water from an upstream chamber 3 m wide × 7 m long and 1.38–3.05 m in depth, depending on experimental slope and headpond level. Water was introduced by gravity flow from an adjacent hydropower canal (Connecticut River) via a valved, 91-cm diameter pipe through the concrete floor of the flume.

Experiments were conducted in 1995 (16 May to 12 June) at slopes of 1:6 (16.7%) and 1:8 (12.5%) and in 1996 (24 May to 20 June) at slopes of 1:10 (10%), 1:4 (25%), and 1:8. Because of limitations on availability of fish during 1996, we elected not to test at 1:6 slope during that year, but ran 6 trials on 1:8 slope (high headpond only) to compare performance of fish under similar hydraulic conditions between years. Water temperatures ranged from 14.0°C to 21.3°C in 1995 and from 15.9°C to 21.1°C in 1996. Headpond level (measured from the water surface to the fishway invert (floor of the fishway at its upstream end) was set at nominal high (107 cm: Denil; 91 cm: steeppass) or low (76 cm: Denil; 61 cm: steeppass) levels. The low headpond level test condition in the Denil fishway was necessarily greater than the U.S. Fish and Wildlife Service recommended minimum operating level (61 cm) to achieve the 61-cm minimum level in the deepened steeppass fishway while operating both fishways simultaneously. Tailwater level (fishway entrance depth) was maintained at 1.22 m for all tests. Because of potential effects of increasing water temperatures, day length, et cetera, on passage performance during the experimental season, treatments were al-

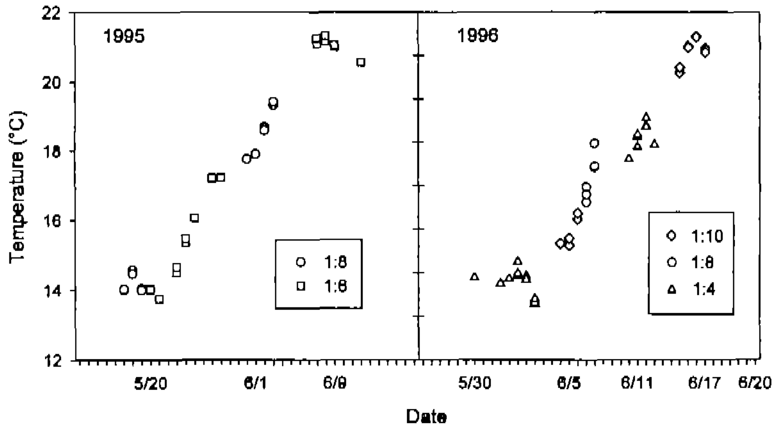


FIGURE 2.—Time series of temperatures during testing in 1995 and 1996. Chronology of testing at different slopes is indicated by the symbols, defined in the key.

ternated and staggered throughout the season to approximate a temporally randomized block experimental design (Figure 2). Fishway slopes were changed every 6–14 trials, and headpond levels were altered every 1–3 trials.

*Fish collection and passage monitoring.*—Upstream migrant American shad and blueback herring were collected from a trap at the exit of an operational fishway on the Connecticut River approximately 1 km from the CAFRC flume facility. Fish were transported to the flume facility via a truck-mounted 1,000-L tank, tagged, and held for testing in open, circulating-water holding ponds (Burrows and Chenoweth 1970).

We used an application of passive integrated transponder (PIT) technology (Texas Instruments TIRIS Series 2000 readers and model RI-TRP-WB2B-03 read/write PIT tags) to monitor volitional movements of individual upstream-migrant American shad and blueback herring. The PIT tags were fitted with #6 hooks and attached to fish by insertion of the hook through the cartilage at the base of the dorsal fin before release of fish in the holding ponds. Four PIT antennas were placed within each fishway; one at the entrance, one at the exit, and two at evenly spaced intermediate locations between the entrance and exit. For further details of the PIT system design and operation, see Castro-Santos et al. (1996).

At the start of each trial, groups of tagged fish were crowded from the holding ponds into the flume below each fishway and allowed to volitionally encounter the fishway for 3 h. An effort was made to include a minimum of 10 fish of each species in each group; most trials were run with a group-size of 20 fish. The 10-fish group-size minimum was not always achieved for blueback herring because of their limited availability at the fishway trap. Movements of fish were recorded by the PIT tag monitoring system, which logged fish identification number and position of the fish (within 0.5 m of each antenna) along with a time stamp (nearest 0.05 s). At the end of the trial, the flume was drained and fish were removed from the test area. The tag number, passage status (above, below, or inside the fishway), fork length (FL), and sex (American shad only) of each fish was recorded. Fish were returned to the river after removal of the tag. A minimum of six trials was run for each treatment condition (slope, headpond, and fishway type). Water temperature was recorded (nearest 0.1°C) hourly during trials; mean temperature was calculated for each trial.

*Data analysis.*—The fish collection (species, length, sex, fish tag code) and passage data (fishway, slope, headpond, temperature, and time of detection at each antenna) were compiled into a single database with each record marked with additional trial identifiers. The data were then sorted by trial, fishway, slope, headpond, tag code, position, and time, yielding a complete time series data set on the passage (or passage attempt) of each individual. Trials with groups of less than 10 introduced fish were omitted from analyses of percent passage. The data were then analyzed to generate percent of the total number of introduced fish passed per trial, and transit time (duration of time from the last PIT tag record from the antenna at the bottom of the fishway to the first record at the antenna at the top of the fishway) for each fish passed.

All effects of slope, headpond, temperature, and

TABLE 1.—Sample sizes ($N$) of data collected for each treatment (slope, headpond), 1995 and 1996 data pooled. Values for percent passage are number of trials with groups of 10 or more American shad or blueback herring; values for transit time are number of individual fish that completed the passage.

| | | Denil | | | | Steeppass | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Shad | | Herring | | Shad | | Herring | |
| Slope | Headpond | Percent passage | Transit time | Percent passage | Transit time | Percent passage | Transit time | Percent passage | Transit time |
| 1:10 | High | 8 | 96 | | | 8 | 101 | | |
| | Low | 7 | 87 | | | 7 | 68 | | |
| 1:8 | High | 12 | 100 | 3 | 16 | 12 | 164 | 3 | 28 |
| | Low | 7 | 76 | 3 | 27 | 7 | 56 | 4 | 23 |
| 1:6 | High | 8 | 40 | 2 | 7 | 7 | 70 | 2 | 9 |
| | Low | 10 | 91 | 1 | 16 | 10 | 62 | 1 | 5 |
| 1:4 | High | 11 | 23 | | | 11 | 100 | | |
| | Low | 8 | 30 | | | 8 | 21 | | |

between-year differences on percent passage and transit time were analyzed using covariance analysis (Proc GLM, SAS 1985). Differences between individual slopes and within-cells differences due to slope × headpond interaction were analyzed using single degree-of-freedom contrasts. The effect of sex on passage in each fishway was analyzed by calculating percent passage of each sex within each trial and performing a Wilcoxon matched-pairs test with percent passage of males and females within each trial as the bivariate random variables (Conover 1980). Only trials with a minimum number of six fish of either sex were used in these analyses.

## Results

In 1995, 1,232 American shad (310–585 mm FL; mean = 413 mm FL) and 424 blueback herring (205–290 mm FL; mean = 234 mm FL) were collected and tested (introduced into the flume). In 1996, 1,521 American shad (305–580 mm FL; mean = 418 mm FL) and 38 blueback herring (220–265 mm FL; mean = 242 mm FL) were collected and tested. Water temperatures ranged between 14°C and 21°C in 1995 and between 15°C and 21°C in 1996.

Sample sizes for percent passage and transit time of trials included in analyses are given in Table 1. Water temperature was positively correlated with percent passage of American shad in both fishways (Figure 3; Denil: $P < 0.001$; steeppass: $P = 0.003$) All subsequent data analyses were performed using complete regression models that included slope, headpond, temperature, and (where significant) year and temperature × year (interaction) effects. Water temperature did not significantly affect percent passage of blueback herring (Denil: $P > 0.05$; steeppass: $P > 0.05$). Water temperature did influence the transit time of both American shad and blueback herring, with shorter transit times associated with higher temperatures (Figure 3; Denil American shad: $P < 0.001$; steeppass American shad: $P < 0.001$; Denil blueback herring: $P = 0.003$; Steeppass blueback herring: $P = 0.065$). Although no significant difference in percent passage was observed between years (Denil: $P > 0.05$; steeppass: $P > 0.05$), transit time did differ between years, with longer transit times associated with 1996 data ($P < 0.001$; steeppass: $P = 0.023$). Moreover, the effect of temperature on transit time for American shad differed between years, with a greater reduction in transit time associated with the 1996 data (Denil: $P < 0.001$; steeppass: $P = 0.028$). Because significant effects of temperature on percent passage and of temperature, year, and temperature × year (interaction) on transit time were observed, these effects were included in the regression models; Figures 4 and 5 reflect least-squares means with these effects adjusted to their mean value.

### *Denil Fishway—American Shad*

Percent passage of American shad decreased with increasing slope ($P < 0.001$; Figure 4a), although the difference was not significant among all slopes. Percent passage was significantly greater at low headpond than at high headpond ($P < 0.001$). Transit time decreased with increasing slope ($P < 0.001$; Figure 5a), but there was no significant difference in mean transit time between 1:4 and 1:6 slopes ($P > 0.05$). Transit time was significantly greater at low headpond than at high headpond ($P < 0.001$). There was no significant difference in percent passage between males and females ($P > 0.05$) in the Denil fishway.

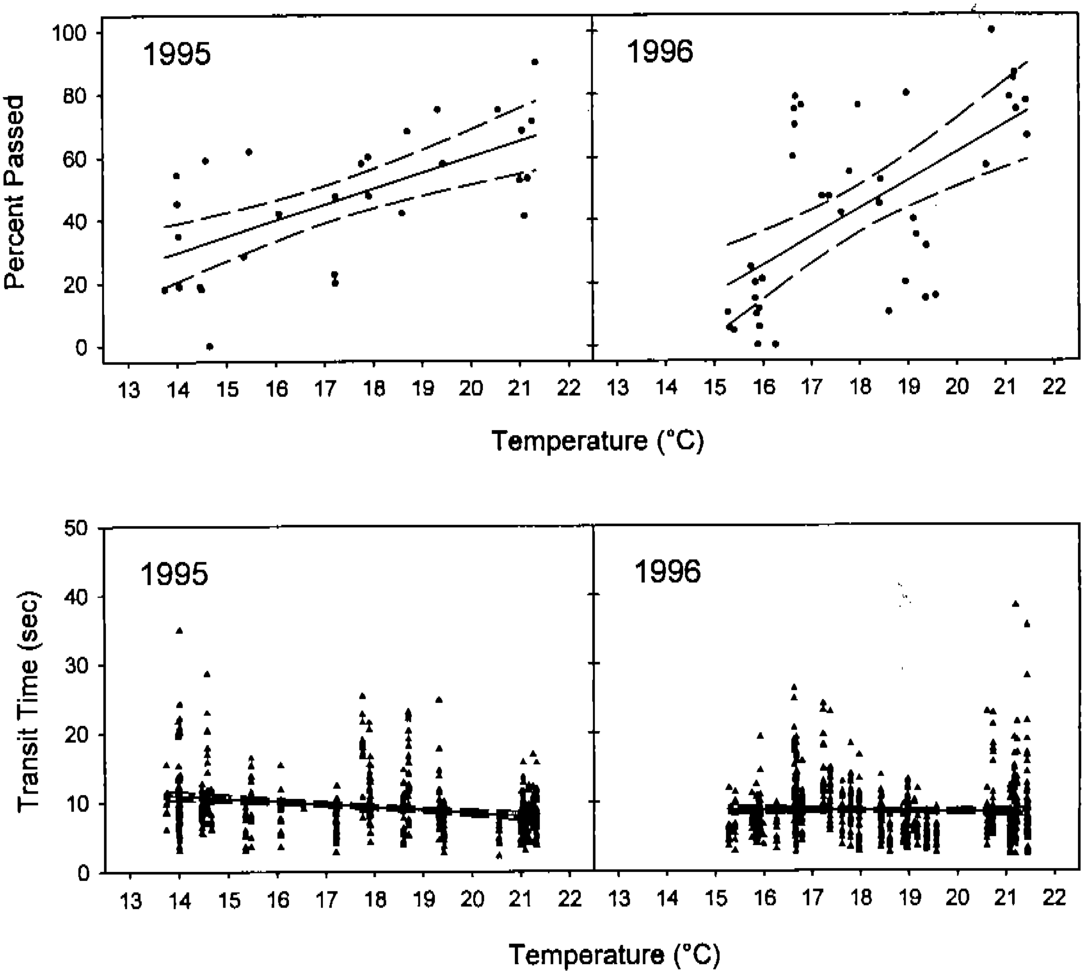


FIGURE 3.—Upper panel: percent of fish passed during each 3-h run versus temperature for comparative 1995 and 1996 tests. Lower panel: transit time of passed fish versus temperature. Both panels illustrate data from Denil fishway, American shad only. Solid lines indicate least-squares regression; dashed lines are 95% confidence limits for each regression.

*Denil Fishway—Blueback Herring*

Percent passage and transit time of blueback herring were not significantly different between slopes ($P > 0.05$) or headpond levels ($P > 0.05$; Figures 4c and 5c).

*Steeppass Fishway—American Shad*

Percent passage of American shad decreased with increasing slope ($P < 0.001$; Figure 4b), and mean percent passage was significantly different between all slopes ($P < 0.05$). Percent passage was significantly greater at high headpond level than at low headpond level ($P < 0.001$). The effect of slope on percent passage was significantly different between headpond levels (i.e., significant interaction; $P < 0.05$). Transit time decreased with increasing slope ($P < 0.001$; Figure 5b), but mean transit times were not significantly different between the 1:8 and 1:10 slopes ($P > 0.05$). Transit time was significantly greater at low headpond than at high headpond ($P < 0.001$). The effect of headpond on transit time was significantly different between slopes (slope × headpond interaction; $P < 0.001$). Percent passage of males was significantly greater than percent passage of females ($P = 0.034$) in the steeppass fishway.

*Steeppass Fishway—Blueback Herring*

Percent passage of blueback herring was greater at 1:8 than at 1:6 slope ($P = 0.016$; Figure 4d),

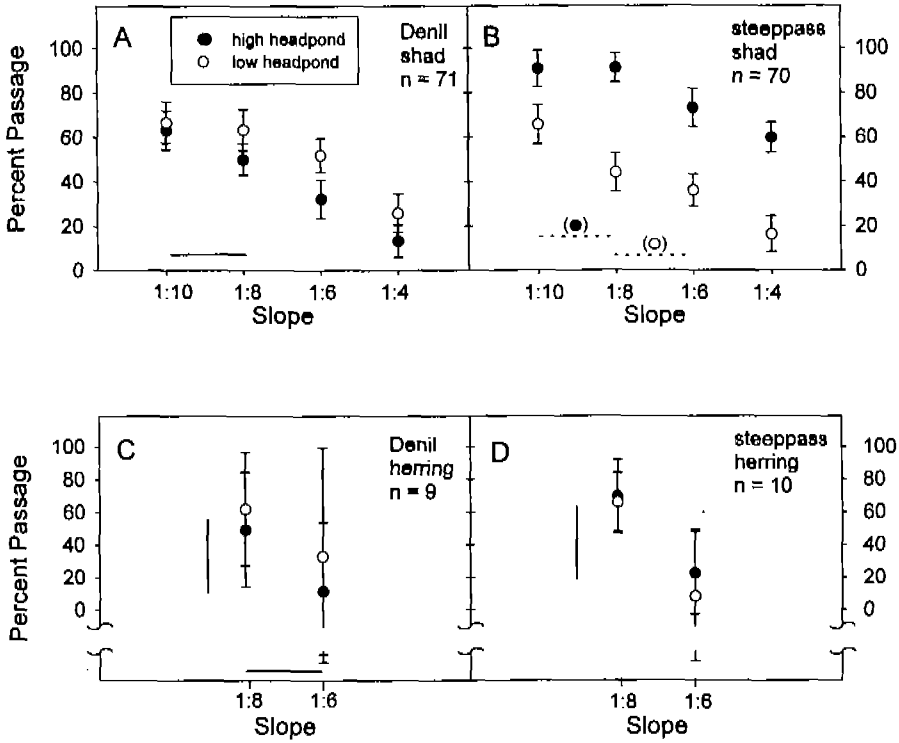


FIGURE 4.—Least-squares mean percent passage versus slope for high (closed circles) and low (open circles) headponds for American shad in the (A) Denil and (B) steeppass fishways and for blueback herring in the (C) Denil and (D) steeppass fishways. Data are means adjusted for temperature. Solid bars indicate no significant difference between pairs of conditions (main effects; horizontal bar = slope, vertical bar = headpond). Dotted bars indicate no significant difference between pairs of conditions within cells where significant slope × headpond interactions existed. Data for blueback herring at 1:6 slope are from 1995 tests only; blueback herring data on 1:8 slope are pooled from 1995 and 1996 tests.

but was not significantly different between low and high headpond levels ($P > 0.05$). Transit time was greater at 1:8 than at 1:6 slope ($P = 0.038$; Figure 5d), but was not significantly different between low and high headpond levels ($P = 0.086$)

## Discussion

Temperature had a pronounced effect on observed passage performance. Percent of American shad passed increased with temperature, whereas transit times decreased with increasing temperature for both species. These results are probably related to increased motivation, physiological capacity, or both, at higher temperatures. Limited sample sizes, incompletely randomized experimental designs, and difference in experimental temperature range between 1995 and 1996 tests probably contributed to a large portion of the variability and interaction of these temperature and year effects. Due to run timing, our tests of blueback herring also occurred over a smaller temperature range than that of American shad. Other sources of variability in results between years might include spawning condition and total time previously spent within the freshwater environment. Because the source of fish used in the tests is 198 km from the river mouth, annual variability in river flows, temperatures, or passage conditions might produce inter-annual differences in fish condition and energy reserves in fish collected from the Cabot fishway trap.

Increasing fishway slope decreased percent passage of American shad, regardless of fishway type. Higher fishway slope decreased percent passage of blueback herring in the steeppass fishway only; however we did not evaluate this effect for blueback herring in the Denil fishway at 1:10 and 1:4 slopes. For American shad in the Denil fishway and steeppass fishway at high headpond, there did not appear to be a strong difference in percent passage between 1:10 and 1:8 slopes, but higher slopes decreased percent passage significantly.

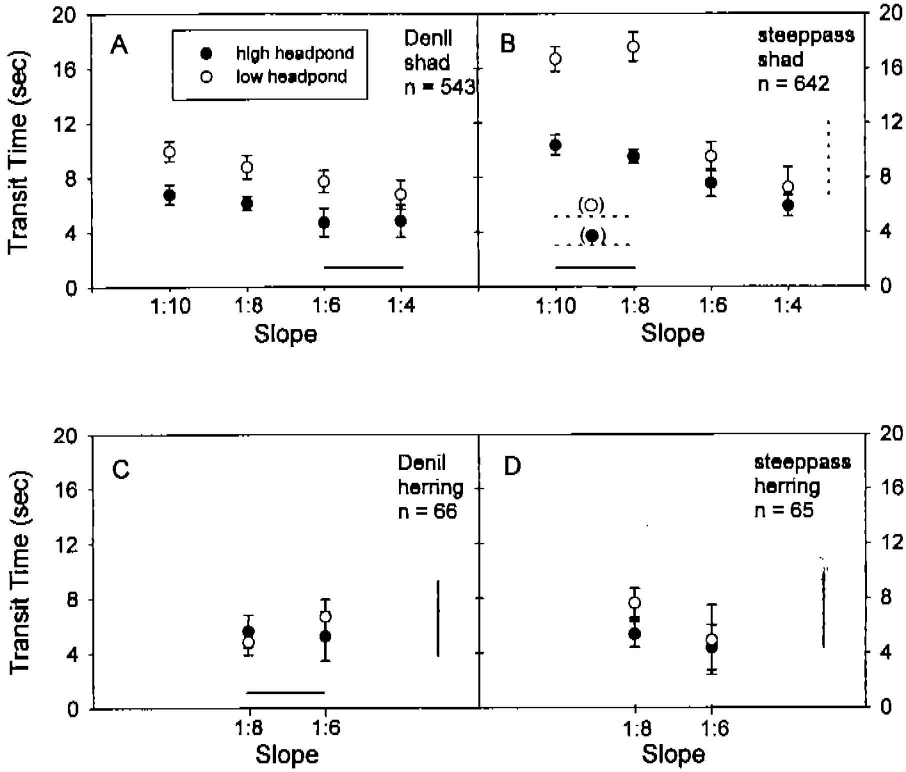


FIGURE 5.—Mean transit time versus slope for high (closed circles) and low (open circles) headponds for American shad in the (A) Denil and (B) steeppass fishways and for blueback herring in the (C) Denil and (D) steeppass fishways. Data are means adjusted for covariates (temperature, year, temperature × year). Solid bars indicate no significant difference between pairs of conditions (main effects; horizontal bar = slope, vertical bar = headpond). Dotted bars indicate no significant difference between pairs of conditions within cells where significant slope × headpond interactions existed. Data for blueback herring at 1:6 slope are from 1995 tests only; blueback herring data on 1:8 slope are pooled from 1995 and 1996 tests.

However, differences in percent passage were significant between 1:10 and 1:8 slopes for American shad in the steeppass fishway at low headpond.

Low headpond increased percent passage of American shad in the Denil fishway, but decreased percent passage of American shad in the steeppass fishway. In both fishways, water energy loss was generated by baffling, which resulted in strong secondary flows and air entrainment in the fishways. At high headpond in the Denil fishway, fluctuating secondary flows created more turbulence and air entrainment, which appeared to hinder passage efficiency of American shad. In contrast, the steeppass baffling did not increase turbulence and air entrainment significantly between high and low headponds. At a given slope, the magnitude of longitudinal velocities within each fishway are similar at both high and low headpond. Therefore, turbulence and air entrainment may influence percent passage of American shad more than longitudinal water velocity. Because headpond level in the steeppass fishway affected percent passage of American shad but not the smaller blueback herring, the relatively small cross-sectional area of the steeppass fishway operated at low headpond may inhibit passage of larger species such as American shad.

Transit time of American shad decreased with both increasing slope and headpond. American shad therefore increased swimming speed under these conditions. Shorter transit times also were not associated with increased percent passage. American shad appeared to regulate their swimming speed through Denil-type fishways below maximal values. Recorded burst speeds for allis shad *A. alosa* range from 4.1 to 6.1 m/s (Larinier and Travade 1992). At the highest average water velocities in the steeppass and Denil fishways (1.8–2.1 m/s), American shad ascended at minimum transit times of approximately 4 s. Over the

6-m distance between PIT tag antennas, these transit time data translate to a through-water swimming speed of 3.4–3.6 m/s for American shad. Surprisingly, blueback herring ascended the fishways at speeds comparable to those of American shad, even though blueback herring average 56% smaller (in fork length) than American shad.

Male American shad also ascended the steeppass fishway in greater proportions than females. The reason for this result is unclear, although smaller males may be able to negotiate the relatively narrow width of the steeppass fishway more easily than larger females. Differential selection of sexes in fishways has been observed for alewives *A. pseudoharengus* ascending a pool and weir fishway (Walton 1982).

The relationships observed for percent passage and transit time are probably the primary result of water velocity and turbulence within each fishway. However, other effects such as air entrainment, visibility, and the hydraulic gradient force (Behlke 1991) could have significant influences on motivation, swimming performance, control, and maneuverability for these and other species. Further detailed analysis of hydraulic characteristics of both fishway types and finer resolution of movements and position of fish within the fishway may yield additional information about these factors and relationships.

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