

O SCALE MODEL RAILROADING

CIVIL & STRUCTURAL ENGINEERING

UPPER-DIVISION LAB SUPPLEMENT

Junior Year | Upper-Division Elective | Full Math Prerequisites Assumed

Structural Analysis · Geotechnical Engineering · Transportation Engineering
Hydraulics & Drainage · Construction Management · Engineering Ethics

O Scale STEM Education Initiative

Series Title	The Railroad as Infrastructure: Civil & Structural Engineering Through O Scale
Target Students	Junior Civil & Structural Engineering — Year 3, Upper-Division Elective Lab Supplement
Prerequisites	Statics; Mechanics of Materials; Fluid Mechanics; Probability & Statistics; Calculus III; Linear Algebra
Format	Six independent Lab Modules — each 2.5–3 hours; each supplements a specific junior CE course
Lab Module 1	Structural Analysis & Load Rating — Influence Lines, Moving Loads & Bridge Rating
Lab Module 2	Geotechnical Engineering — Track Modulus, Settlement Analysis & Bearing Capacity
Lab Module 3	Transportation Engineering — Capacity Analysis, Signal Timing & Schedule Reliability
Lab Module 4	Hydraulics & Drainage — Culvert Design, HGL Analysis & Scour
Lab Module 5	Construction Management — CPM Scheduling, EVM & Schedule Compression
Lab Module 6	Engineering Ethics & Failure Analysis — Professional Responsibility & Risk Assessment
Capstone	Comprehensive Railroad Infrastructure Assessment — Full Engineering Report
Scale	O Scale (1:48) — all model data scaled to prototype; compared to AREMA/AASHTO/FRA standards
Codes Applied	AREMA Manual; AASHTO LRFD; ASCE 7; FRA 49 CFR Part 213; FHWA HEC-18/22

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Curriculum Philosophy: Each lab module treats the O Scale model railroad as a 1:48 scale civil infrastructure system. Every experiment generates real measured data that students scale to prototype and compare to published AREMA, AASHTO, and FRA standards. The mathematics is identical to professional practice: calculus-based derivations, stiffness matrix structural analysis, stochastic simulation, reliability index calculations, and earned value project controls. The model makes abstract infrastructure engineering physically tangible and measurable.

ABET & ASCE Body of Knowledge Coverage

Standard/Code	Core Idea / Competency	How the O Scale Lab Addresses It
ABET (1)	Identify, formulate, and solve complex engineering problems	Every module requires formal problem formulation, derivation-based solution, and experimental verification
ABET (2)	Apply engineering design within realistic constraints	Module 6 integrates all constraints; Module 5 adds cost/schedule; Module 4 adds environmental constraints
ABET (3)	Communicate effectively in written and oral forms	Each module requires a formal lab report; capstone is a complete engineering assessment document
ABET (4)	Recognize ethical and professional responsibilities	Module 6 explicitly addresses failure analysis, whistleblower ethics, and the duty to public safety
ABET (6)	Design and conduct experiments; analyze and interpret data	Six experiment sets — all require error propagation, statistical analysis, and comparison to theory
ABET (7)	Acquire and apply new knowledge independently	Each module requires students to read and apply one AREMA/AASHTO standard independently
ASCE BOK2 Outcome 7	Breadth across all CE subdisciplines	Modules 1–6 cover structures, geotech, transportation, water resources, and construction management

LAB MODULE 1

Structural Analysis & Bridge Load Rating

Influence Lines, Moving Loads, Cooper E Loading & AREMA Load Rating

Recommended Supplement: CE 3XX Structural Analysis | CE 4XX Bridge Engineering

Duration	3 hours (1 hr theory + 2 hr experimental)
Prerequisites	Statics; Mechanics of Materials; ability to solve systems of linear equations
Core Concepts	Influence lines (Müller-Breslau principle), absolute maximum moment under moving loads, Cooper E loading, AREMA load rating factor RF, stiffness matrix method, virtual work deflection
Math Required	Integration (virtual work), matrix methods (stiffness K assembled from element matrices), calculus-based moment equations
Codes Applied	AREMA Manual Chapter 15 (steel structures); Cooper E-60 and E-80 loading definitions
Driving Question	Given a model bridge of known geometry and material, can you determine the load rating — the maximum train weight this bridge can safely carry — using the same method a practicing bridge engineer uses?

Theory — Influence Lines & Moving Loads

An influence line (IL) shows how a structural response quantity (reaction, shear, moment) varies as a unit load traverses the span. For a simply supported beam of span L , the IL ordinate for midspan moment at load position a :

$$\eta_M(a) = a(L-a)/(2L) \quad \text{for } 0 \leq a \leq L/2 \quad [\text{symmetric about midspan}]$$

The maximum moment under a group of moving concentrated loads is found when: the resultant of all loads and the load nearest the resultant are equidistant from midspan (absolute maximum moment theorem). Students apply this to scaled Cooper E-60 axle loads.

Cooper E Loading — Scaling to O Scale

Cooper E-80 maximum axle = 80 kips = 80,000 lbs. Weight scales as cube of linear ratio $(1/48)^3 = 1/110,592$:

$$\text{Model axle load} = 80,000 / 110,592 = 0.723 \text{ lbs} = 328 \text{ grams}$$

Students verify by weighing actual O Scale locomotives. Axle spacing scales linearly (1:48). Students construct a paper cutout of the scaled Cooper axle group at correct spacings for use in the moving load experiment.

Stiffness Matrix — Two-Span Continuous Bridge

For a prismatic beam element (length L , rigidity EI), the 4×4 element stiffness matrix in local coordinates:

$$[k] = (EI/L^3) * \begin{bmatrix} 12 & 6L & -12 & 6L \\ 6L & 4L^2 & -6L & 2L^2 \\ -12 & -6L & 12 & -6L \\ 6L & 2L^2 & -6L & 4L^2 \end{bmatrix}$$

Assemble the global [K] by superimposing element matrices at shared DOFs. Apply boundary conditions. Solve $[K]\{d\}=\{F\}$ for displacements {d}. Recover member forces from {d}.

AREMA Load Rating Factor

$$RF = (C - A1*D) / (A2*L)$$

C = capacity (allowable stress x section modulus); D = dead load effect; L = live load effect; A1 = A2 = 1.0 (allowable stress method). RF >= 1.0 means the bridge passes for that Cooper level.

Laboratory Procedure

Part 1A — Experimental Influence Line (45 min)

Place a 100g calibrated weight at $x = 0.1L, 0.2L \dots 0.9L$ across the model bridge span. At each position record both support reactions using digital scales (tared to zero with bridge dead load). Calculate midspan moment from equilibrium. Plot measured vs. theoretical IL ordinates. Percent error at each point.

Part 1B — Moving Load Train Simulation (30 min)

Simulate Cooper E-60 traversal by sequentially positioning the scaled axle load cutout and recording midspan moment at each position. Plot the moment envelope. Identify the critical train position producing absolute maximum moment. Compare to the analytical prediction from the absolute maximum moment theorem.

Part 1C — Deflection by Virtual Work & Coupon Test (30 min)

Measure bridge material E using a cantilever coupon test: clamp a sample strip, apply known tip load P, measure tip deflection delta. Back-calculate $E = PL^3/(3*\delta*I)$. Predict bridge midspan deflection under scaled Cooper load using $\delta = PL^3/(48EI)$. Measure actual deflection with a dial indicator. Calculate percent error and identify sources of discrepancy.

Part 1D — FEA Comparison & Load Rating (15 min)

Input bridge geometry into SkyCiv free truss/frame calculator. Compare FEA moment and deflection to hand calculations. Calculate RF for Cooper E-60. Write a one-paragraph load rating finding in AREMA bridge inspection format: structure, rating level, RF value, controlling limit state, recommendation.

Assessment — Lab Module 1

Criterion	4 – Exemplary	3 – Proficient	2 – Developing	1 – Beginning
Influence Line	Theoretical IL derived analytically for all 9 positions; experimental IL plotted with error bars; percent error < 8%; critical position identified with explanation	Theoretical IL correct; experimental IL plotted; percent error calculated; critical position identified	Theoretical IL partially correct; midspan error only	IL not derived analytically; experimental data not compared to theory
Moving Load Envelope	Moment envelope plotted for full traversal; critical position identified with calculation; compared to uniform load case with explanation	Envelope plotted; critical position identified; uniform load comparison attempted	Moment at several positions; no envelope	Moment at one or two positions only
Virtual Work & Coupon	E measured from coupon with uncertainty; deflection predicted; compared to FEA and measurement; discrepancies analyzed	E measured; deflection predicted; compared to FEA; errors listed	Deflection formula applied; E assumed; no FEA comparison	Formula applied without measured E; no comparison
Load Rating RF	RF correct using AREMA method; pass/fail stated; sensitivity to one key parameter shown; finding written in professional format	RF correct; pass/fail stated; one sensitivity case	RF calculated with minor errors; pass/fail stated; no professional format	RF formula stated but not correctly calculated
Report Quality	ASCE format: abstract, theory with derivations, procedure, data, error analysis, conclusions with code references, raw data appendix	Complete; error propagation partially addressed	Present but informal; theory section incomplete	Lab notes only; no professional structure

LAB MODULE 2

Geotechnical Engineering & Track Subgrade

Track Modulus, Beam on Elastic Foundation, Settlement & Bearing Capacity

Recommended Supplement: CE 3XX Geotechnical Engineering | CE 4XX Foundation Engineering

Duration	3 hours (1 hr theory + 2 hr lab)
Prerequisites	Soil Mechanics; Fluid Mechanics; Calculus III (PDE for consolidation)
Core Concepts	Track modulus u (Winkler foundation), beam on elastic foundation ODE, characteristic length L_c , Terzaghi bearing capacity, 1D consolidation settlement, ballast gradation and USCS classification
Math Required	4th-order ODE solution, integration (consolidation settlement), Mohr-Coulomb failure criterion, log-normal probability (for settlement reliability extension)
Codes Applied	AREMA Manual Chapter 1 (roadway and ballast); FRA Track Safety Standards 49 CFR Part 213 — cross-level and surface limits for Track Classes 1–5
Driving Question	The railroad track is not just steel rails and ties — it is a structural system on an engineered foundation. How does the soil beneath the track govern the load that can be safely carried at speed?

Theory — Beam on Elastic Foundation (Winkler Model)

The rail behaves as an infinite beam on an elastic foundation. Governing ODE for rail deflection $y(x)$ away from the load point:

$$EI \cdot \frac{d^4y}{dx^4} + u \cdot y = 0$$

Where EI = rail flexural rigidity; u = track modulus (lb/in/in). Solution yields characteristic length:

$$L_c = (4EI/u)^{1/4}$$

Deflection basin under point load P :

$$y(x) = (P \cdot L_c) / (8EI) \cdot e^{-(|x|/L_c)} \cdot \cos(|x|/L_c)$$

Maximum deflection at load point: $y_{\max} = P \cdot L_c / (8EI)$. Track modulus u is back-calculated from measured y_{\max} .

Physical Significance: Low track modulus causes excessive dynamic amplification. At speed, the rail rebounds behind the wheel and impacts the trailing wheel with $DAF = 1 + 0.33 \cdot V / \sqrt{D}$ where V is speed (mph) and D is wheel diameter (in). FRA limits operating speed by track class precisely because high-speed dynamic loading on soft subgrade causes rapid degradation.

Terzaghi Bearing Capacity — Tie on Ballast

$$q_{ult} = c \cdot N_c + q \cdot N_q + 0.5 \cdot \gamma \cdot B \cdot N_{\gamma}$$

For railroad subgrade ($\phi = 25$ deg, $c = 0$): $N_c = 25.1$, $N_q = 12.7$, $N_{\gamma} = 9.7$. Allowable = $q_{ult} / 3.0$ (AREMA FoS). The model tie is treated as a strip footing (width $B = 0.25$ in, length $L = 1.25$ in).

Terzaghi 1D Consolidation Settlement

$$dU/dt = c_v * d^2U/dz^2 \quad [\text{consolidation PDE}]$$

$$S_c = (C_c / (1 + e_0)) * H * \log_{10}(\sigma_f / \sigma_0)$$

$$t_{90} = T_{90} * H_{dr}^2 / c_v \quad \text{where } T_{90} = 0.848$$

Laboratory Procedure

Part 2A — Track Modulus Measurement (40 min)

Measure rail deflection under the O Scale locomotive (weighed before lab) at 4 locations on the layout using a dial indicator on the rail head. Back-calculate $u = P / (2 * y_{max} * L_c * 2)$ iterating on $L_c = (4EI/u)^{1/4}$. Report mean and standard deviation of u . Plot measured deflection basin at best and worst locations vs. Winkler prediction $y(x)$.

Part 2B — Ballast Gradation & Bearing Capacity (35 min)

Receive three samples: (A) well-graded crushed granite; (B) poorly-graded fine sand; (C) silty clay. Perform sieve analysis or ASTM visual classification. Plot gradation curves. Classify by USCS. Evaluate against AREMA Chapter 1 ballast specification. Load model tie on each sample with calibrated weights to bearing failure. Calculate $FoS_{achieved} = \text{measured failure load} / \text{theoretical } q_{ult} \times B \times L$.

Part 2C — Consolidation Settlement & FRA Limit (30 min)

Given soft clay subgrade properties ($C_c=0.35$, $e_0=1.10$, $H=8$ ft prototype, $c_v=0.02$ in²/min): Calculate S_c under Cooper E-80 surcharge. Calculate t_{90} . Scale model settlement: if observed, would FRA Class 4 cross-level limit of 1.25 inches be exceeded? Propose one ground improvement strategy (surcharge, vertical drains, or chemical stabilization) and quantify its effect on either S_c or t_{90} using equations.

Assessment — Lab Module 2

Criterion	4 – Exemplary	3 – Proficient	2 – Developing	1 – Beginning
Track Modulus Analysis	u at 4 locations; mean and 95% CI reported; L_c calculated; deflection basin plotted vs. Winkler theory; spatial variability discussed with physical explanation	u at 3 locations; mean and sigma; L_c calculated; basin plotted	u at 2 locations; mean only; L_c calculated; no basin	u at one location; no statistics; no basin plot
Bearing Capacity	q_{ult} for all 3	q_{ult} for 2	q_{ult} for 1	Formula stated;

	<p>samples using correct N-factors; USCS classification correct; AREMA compliance evaluated; FoS_achieved vs. 3.0 compared</p>	<p>samples; USCS correct; AREMA evaluated</p>	<p>sample; USCS correct; AREMA not applied</p>	<p>not calculated; no USCS</p>
<p>Consolidation Settlement</p>	<p>S_c and t_90 correct with all parameters; scaled to model; FRA 1.25-in limit applied; improvement strategy quantified with equations</p>	<p>S_c and t_90 correct; FRA limit applied; improvement qualitative</p>	<p>S_c correct; t_90 has errors; no FRA limit or improvement</p>	<p>S_c formula used with major errors; no t_90 or FRA</p>
<p>ODE Formulation</p>	<p>Winkler ODE correctly stated; characteristic length derived from solution form; y(x) basin equation stated; physical meaning of L_c explained in terms of load spread</p>	<p>ODE stated; L_c formula given; y(x) stated without derivation</p>	<p>ODE stated; L_c used without derivation</p>	<p>L_c formula used as lookup; ODE not stated</p>
<p>Ballast Gradation</p>	<p>All 3 gradation curves plotted; USCS classifications correct; AREMA specification limits overlaid on plot; non-conforming samples identified with consequence discussion</p>	<p>2 curves correct; USCS correct; AREMA limits shown</p>	<p>1 curve; USCS correct; AREMA not applied</p>	<p>Qualitative description only; no plot</p>

LAB MODULE 3

Transportation Engineering & Rail Capacity

Block Signal Capacity, M/D/1 Queueing, Schedule Reliability & Monte Carlo Simulation
Recommended Supplement: CE 3XX Transportation Engineering | CE 4XX Traffic Operations

Duration	2.5 hours (45 min theory + 1 hr 45 min lab)
Prerequisites	Probability & Statistics; Calculus; Introduction to Transportation Engineering
Core Concepts	Fixed-block capacity, minimum headway, single-track meet-and-pass logic, M/D/1 vs M/M/1 queueing, FOSM reliability index beta, Monte Carlo schedule simulation
Math Required	Probability distributions (Poisson, normal), queueing formulas, FOSM (first-order second-moment reliability), Monte Carlo simulation in spreadsheet
Codes Applied	FRA 49 CFR Part 236 (signal systems); TRB Report TR-182 (railroad capacity)
Driving Question	How many trains per hour can safely operate on a single-track railroad — and what happens to that number when you add a passing siding? Derive it analytically, then verify by live operation.

Theory — Block Signal Capacity & Headway

$$H_{\min} = t_{\text{block}} + t_{\text{clear}} + t_{\text{approach}}$$

$$C_{\max} = 3600 / H_{\min} \quad [\text{trains/hour, one direction}]$$

For single-track with meets (TRB formula):

$$C_{\text{ST}} = 60 * L / (t_{\text{run}} + t_{\text{meet}} * (N_{\text{siding}}) / (N_{\text{siding}} + 1))$$

M/D/1 vs M/M/1 — Scheduled vs. Random Service

$$W_q(M/M/1) = \rho / (\mu * (1 - \rho))$$

$$W_q(M/D/1) = \rho / (2 * \mu * (1 - \rho))$$

Railroad scheduled service more closely follows M/D/1 (deterministic service intervals), giving 50% lower queuing delays at same utilization. Students apply both and determine which better matches observed data.

FOSM Reliability Index for On-Time Performance

$$Z = T_{\text{allowed}} - T_{\text{actual}}$$

$$\beta = \mu_Z / \sigma_Z = (\mu_{T_{\text{allowed}}} - \mu_{T_{\text{actual}}}) / \sqrt{\sigma^2_{\text{allowed}} + \sigma^2_{\text{actual}}}$$

$$P(\text{on-time}) = \Phi(\beta)$$

Laboratory Procedure

Part 3A — Headway & Block Capacity Measurement (30 min)

Define two fixed blocks. Time minimum safe headway over 10 consecutive train movements. Calculate H_{min} (mean), C_{max} . Compare to observed throughput in 15-min window. Compute utilization $\rho = \text{observed} / C_{max}$.

Part 3B — Single-Track Capacity with Siding (45 min)

Operate bi-directional trains with one passing siding. Record: meet-and-pass delay (10 meets), end-to-end running time (each direction, 5 runs), total train-movements in 30 min. Apply TRB formula with measured inputs. Simulate adding a second siding by reducing meet delay 40% and recalculate. Quantify capacity increase in trains/hour.

Part 3C — Monte Carlo Schedule Reliability (45 min)

From Part 3A/3B measurements: record μ_T and σ_T for travel time. Run 200-iteration Monte Carlo simulation in spreadsheet: each iteration draws $N(\mu_T, \sigma_T^2)$, checks vs. schedule window. Calculate: $P(\text{on-time})$ from simulation; compare to $\Phi(\beta)$ from FOSM. Plot $P(\text{on-time})$ vs. schedule slack from $\mu_T - \sigma_T$ to $\mu_T + 3\sigma_T$. Identify slack for $P = 0.95$. Calculate annual revenue cost of that slack if each lost train-slot = \$5,000/day.

Assessment — Lab Module 3

Criterion	4 – Exemplary	3 – Proficient	2 – Developing	1 – Beginning
Headway & Capacity	H_{min} from 10 measurements with 95% CI; C_{max} derived; compared to observed with explanation; ρ calculated	H_{min} and C_{max} correct; ρ calculated; comparison to observation	H_{min} calculated; C_{max} stated; no comparison	Headway concept stated; not calculated from data
TRB Capacity Formula	Applied for 0, 1, and 2 sidings with measured inputs; capacity increase per siding quantified; compared to observed throughput	Applied for 0 and 1 siding; compared to observation	Applied for 1 siding; no comparison	Formula stated but not applied with measured parameters
FOSM Reliability	β calculated with measured μ_T and σ_T ; $P(\text{on-time}) = \Phi(\beta)$ computed; compared to	β and $P(\text{on-time})$ correct; Monte Carlo comparison attempted	β formula applied; parameters estimated; no Monte Carlo	β not calculated; reliability analysis absent

	Monte Carlo			
Monte Carlo Simulation	200+ iterations; P(on-time) vs. slack plotted; P=0.95 slack identified; revenue cost calculated; FOSM agreement assessed	100+ iterations; plot produced; P=0.95 identified; no revenue	50+ iterations; P(on-time) at one slack; no plot	<50 iterations or simulation setup only
M/D/1 vs M/M/1	Both formulas applied with measured lambda and mu; W _q compared; better model identified with justification from data	Both applied; models compared; identification made	One formula applied; comparison attempted	Neither applied with measured data

LAB MODULE 4

Hydraulics & Drainage Engineering

Culvert Design, HGL Construction, Scour Analysis & Stormwater Management

Recommended Supplement: CE 3XX Hydraulics & Hydrology | CE 4XX Open Channel Flow

Duration	2.5 hours (45 min theory + 1 hr 45 min lab)
Prerequisites	Fluid Mechanics; Calculus III; Probability & Statistics (frequency analysis)
Core Concepts	Manning's equation, culvert inlet vs. outlet control, Hydraulic Grade Line (HGL), Energy Grade Line (EGL), HEC-18 local scour, Rational Method, log-Pearson Type III frequency analysis
Math Required	Manning's equation, Bernoulli extended (energy equation), Froude number, HEC-18 scour equation, Rational Method, return period probability
Codes Applied	AREMA Chapter 8 (bridge waterway); FHWA HEC-22 (culvert design); FHWA HEC-18 (scour analysis); FRA bridge inspection standards
Driving Question	A 100-year storm threatens the railroad's culvert crossing. Design the culvert to pass the flood safely, estimate abutment scour depth, and determine whether the track remains in service after the storm.

Theory — Manning's Equation & Culvert Control Modes

$$Q = (1/n) * A * R^{(2/3)} * S^{(1/2)} \quad [\text{Manning's equation}]$$

Inlet control: flow is critical at the entrance; HW governed by inlet geometry. Outlet control: tailwater is high enough that the barrel and exit govern. Energy equation (outlet control):

$$HW = TW + V^2/(2g) + H_f - L*S$$

$$H_f = [K_e + (29*n^2*L)/R^{(4/3)}] * V^2/(2g)$$

HEC-18 Local Scour at Bridge Piers

$$y_s/y_1 = 2.0 * K_1 * K_2 * K_3 * K_4 * (a/y_1)^{0.65} * Fr_1^{0.43}$$

y_1 = approach depth; a = pier width; Fr_1 = approach Froude number; K_1 - K_4 = shape, angle, bed condition, armoring factors from HEC-18 Table 7.1.

Laboratory Procedure

Part 4A — Culvert Flow Measurement (40 min)

Build a model culvert crossing (scaled PVC pipe beneath a foam embankment in a plastic flume with controlled inflow). Regulate 3 flow rates. Measure HW, TW, and Q (volumetrically). Calculate Manning's Q; compare to measured. Determine inlet vs. outlet control for each flow rate. Scale to prototype; evaluate against AREMA minimum waterway area.

Part 4B — HGL & EGL Construction (30 min)

At the highest tested flow: plot the HGL from TW through the culvert barrel accounting for friction losses. Add entrance loss to get the headwater HGL. Plot the EGL = HGL + $V^2/(2g)$ above the HGL. Identify where HGL intersects the crown (pressure flow = outlet control confirmed). Recommend the single most cost-effective improvement to increase capacity.

Part 4C — Scour Analysis & FRA Safety Finding (35 min)

Using a provided IDF curve and watershed area: calculate Q_{100} by Rational Method ($Q = C \cdot i \cdot A$). Calculate approach depth y_1 and Froude number Fr_1 . Apply HEC-18 to find local scour depth y_s . Add contraction scour (Richardson & Davis simplified method). Scale total scour to prototype. Compare to assumed foundation depth. Write the FRA bridge inspection finding: if total scour > 50% of foundation depth, a slow order or bridge closure is required. State the finding formally.

Assessment — Lab Module 4

Criterion	4 – Exemplary	3 – Proficient	2 – Developing	1 – Beginning
Culvert Hydraulics	Manning's Q for all 3 flows with % error; control mode determined for each; prototype capacity vs. AREMA minimum evaluated	Manning's Q for 2 flows; control mode for each; prototype calculated	Manning's Q for 1 flow; control mode not determined; no prototype scaling	Manning's equation applied incorrectly
HGL/EGL Construction	HGL complete with entrance loss; EGL plotted above HGL; pressure flow correctly identified; capacity improvement quantified with specific modification	HGL complete; EGL plotted; pressure flow identified; improvement qualitative	HGL plotted without EGL; pressure flow not identified	HGL has major errors in loss calculations
HEC-18 Scour	Local scour with all K-factors; contraction scour added; total scaled to prototype; compared to foundation depth; FRA finding written in professional format	Local scour correct; total scour estimated; scaled; finding written	Local scour only; no FRA finding	HEC-18 parameters not correctly applied

Rational Method	Q_100 correct with IDF curve and appropriate C; used as scour input; return period probability interpreted correctly	Q_100 correct; used as input; return period stated	Q_100 calculated; not propagated to scour	Rational method stated but not applied
Professional Format	FRA finding includes: structure ID, inspection date, flood event, scour depth, foundation depth, consequence, required action, engineer statement	All elements present; minor format issues	Finding present but missing consequence or required action	Informal write-up; not in inspection format

LAB MODULE 5

Construction Management & Project Controls

CPM Scheduling, PERT Analysis, Resource Leveling & Earned Value Management

Recommended Supplement: CE 3XX Construction Engineering | CE 4XX Project Management

Duration	2.5 hours (30 min theory + 2 hr lab)
Prerequisites	Introduction to Engineering Management; Linear Algebra; Probability
Core Concepts	Critical Path Method (CPM), PERT beta distribution, float analysis, schedule compression (crashing), resource leveling, Earned Value Management (EVM): PV, EV, AC, CPI, SPI, EAC
Math Required	Network longest-path algorithm (DAG), expected value (PERT), linear programming (crashing), EVM indices and forecasting formulas
Codes Applied	AASHTO/AGC/ARTBA contract guidelines; FRA Track Maintenance Standards; standard construction General Conditions (delay damages, schedule requirements)
Driving Question	You are the construction manager for a railroad bridge replacement. The owner requires the bridge back in service within 21 days. Build the CPM schedule, identify the critical path, evaluate PERT schedule risk, crash if needed, and track performance with Earned Value — before the first shovel hits the ground.

Theory — Critical Path Method

CPM models a project as a directed acyclic graph. Forward pass calculates Early Start (ES) and Early Finish (EF); backward pass calculates Late Start (LS) and Late Finish (LF). Total Float $TF = LF - EF = LS - ES$. Activities with $TF = 0$ are on the critical path.

$$ES_j = \max(EF_i) \text{ for all predecessors } i$$

$$EF_j = ES_j + \text{Duration}_j$$

$$LF_i = \min(LS_j) \text{ for all successors } j$$

$$LS_i = LF_i - \text{Duration}_i$$

PERT — Probabilistic Durations

$$\mu_D = (a + 4m + b) / 6$$

$$\sigma^2_D = ((b - a) / 6)^2$$

Where a = optimistic, m = most likely, b = pessimistic duration. Project completion variance = sum of variances of critical path activities. $P(\text{complete by date } T) = \Phi((T - \mu_{\text{project}}) / \sigma_{\text{project}})$.

Schedule Compression — Crashing

Crashing adds resources to shorten critical path activities at a cost. Crash cost slope:

$$\text{Cost Slope} = (\text{Crash Cost} - \text{Normal Cost}) / (\text{Normal Duration} - \text{Crash Duration})$$

Optimal crashing: crash the critical path activity with the lowest cost slope first, then reassess the critical path. Continue until schedule target is met or marginal cost exceeds benefit.

Earned Value Management

$CV = EV - AC$ [Cost Variance; negative = over budget]

$SV = EV - PV$ [Schedule Variance; negative = behind schedule]

$CPI = EV / AC$ [Cost Performance Index; < 1.0 = over budget]

$SPI = EV / PV$ [Schedule Performance Index; < 1.0 = behind schedule]

$EAC = BAC / CPI$ [Estimate at Completion, assuming CPI holds]

$ETC = EAC - AC$ [Estimate to Complete]

Laboratory Procedure

Part 5A — Build the CPM Schedule (30 min)

Using the bridge replacement activity list below, students perform the complete CPM forward and backward pass, calculate total float for all activities, identify the critical path, and determine the project duration. Is 21 days achievable?

Activity	Dur (days)	Pred.	ES	EF	LS	LF	TF
1. Site Mobilization & Survey	2	—					
2. Demolish Old Bridge	3	1					
3. Excavate Abutment Foundations	4	2					
4. Dewater & Shore Excavations	2	3					
5. Pour Abutment Footings (cure 3d)	3	4					
6. Fabricate Steel Girders (off-site)	8	2					
7. Form & Pour Abutment Walls	4	5					
8. Backfill & Compact Abutments	2	7					
9. Deliver & Erect Steel Girders	2	6,8					
10. Form & Pour Concrete Deck	3	9					
11. Cure Concrete Deck	4	10					
12. Install Rail, Ballast & Track	2	11					
13. Signal & Electrical Installation	2	12					
14. Final Inspection & Testing	1	13					

Part 5B — PERT Risk Analysis (20 min)

For each critical path activity, students receive three-point estimates (a, m, b). Calculate expected duration and variance for each. Sum critical path expected durations and variances. Calculate $P(\text{complete by day 21})$ and $P(\text{complete by day 25})$. Plot the project completion CDF using the normal approximation.

Part 5C — Schedule Crashing (25 min)

The owner imposes a 17-day completion requirement with a \$2,000/day incentive for early completion. Crash cost and maximum crash durations are provided for each activity. Students: (1) calculate cost slopes; (2) crash the cheapest critical path activity first; (3) reassess critical path after each crash; (4) continue until 17 days is achieved or infeasible; (5) calculate total crashing cost; (6) determine whether the incentive exceeds the crashing cost.

Part 5D — Earned Value Analysis (25 min)

At the end of week 12 of the bridge project, the following status data is given. Students calculate all EVM indices and forecast project final cost and completion date.

Activity	BAC (\$k)	PV (\$k)	EV (\$k)	AC (\$k)	CV / SV / CPI / SPI
Site Mobilization	12	12	12	13	
Demolish Old Bridge	18	18	18	20	
Excavate Foundations	24	24	20	22	
Dewater & Shore	10	10	6	8	
Abutment Footings	20	20	0	0	
Girder Fabrication	85	85	60	72	
TOTALS (Week 12)	169	169	116	135	

For each activity and the project total, calculate: CV, SV, CPI, SPI, EAC, ETC. Interpret: Is the project over budget? Behind schedule? What is the most likely final cost? What is the most likely completion date? Write a one-page executive status report with findings and recommended corrective actions.

Assessment — Lab Module 5

Criterion	4 – Exemplary	3 – Proficient	2 – Developing	1 – Beginning
CPM Forward/Backward Pass	All 14 activities: ES, EF, LS, LF, TF correct; critical path correctly identified; project	ES/EF/LS/LF correct for all; critical path identified; one TF error	Critical path correct; 2-3 float errors	Forward pass only; backward pass incomplete; critical path not identified

	duration correct; logic verified			
PERT Risk Analysis	Expected duration and variance for each critical path activity; project mu and sigma correctly summed; P(21 days) and P(25 days) computed; CDF plotted	mu and sigma correct; P(21) and P(25) computed; no CDF plot	mu correct; sigma has errors; one probability computed	PERT formula stated; not applied to all activities
Schedule Crashing	Cost slopes correct; cheapest-first crashing sequence followed; critical path reassessed after each crash; 17-day feasibility determined; crashing cost vs. incentive evaluated	Cost slopes correct; crashing sequence followed; feasibility determined; incentive comparison made	Cost slopes correct; crashing attempted without reassessing critical path	Cost slope formula stated; not applied to activities
Earned Value Analysis	CV, SV, CPI, SPI, EAC, ETC correct for all activities and totals; completion date forecast; executive report professional with findings and actions	All indices correct; EAC and completion date forecast; report present but informal	CPI and SPI correct; EAC calculated; no completion date forecast; report is bullet list	Some EVM formulas applied; indices have calculation errors
Executive Status Report	One-page report in professional format: project name, data date, budget status, schedule status, CPI/SPI trends, EAC, recommended corrective actions; executive-appropriate language	All elements present; minor format issues; mostly professional language	Report covers budget and schedule; missing EAC or corrective actions; semi-formal language	Informal write-up; EVM numbers listed without interpretation

LAB MODULE 6

Engineering Ethics & Failure Analysis

Professional Responsibility, Forensic Investigation & Risk-Based Decision Making

Recommended Supplement: All Junior CE Courses | CE 4XX Engineering Ethics

Duration	2.5 hours (45 min theory + 1 hr 45 min case analysis + discussion)
Prerequisites	Completion of Lab Modules 1–5 recommended; any junior CE course
Core Concepts	NSPE Code of Ethics, ASCE Code of Ethics, forensic engineering methodology, failure modes and effects analysis (FMEA), risk matrix, probability of failure, whistleblower protection, engineer of record (EOR) responsibility, strict liability vs. negligence
Math Required	Probability of failure $P_f = 1 - \Phi(\beta)$, risk matrix (P x C scoring), fault tree analysis (AND/OR gates), basic Bayes' theorem for posterior failure probability
Codes Applied	NSPE Code of Ethics; ASCE Code of Ethics; AREMA Manual (maintenance of way standards); FRA accident investigation regulations; NTSB accident report methodology
Driving Question	When a railroad bridge fails and trains derail, who is responsible — and how does the engineering profession determine that? More importantly: what should the engineer have done before the failure to prevent it?

Ethical Framework

The NSPE Code of Ethics states in its Fundamental Canon 1: "Engineers shall hold paramount the safety, health, and welfare of the public." This creates a legal and ethical obligation that supersedes employer loyalty, economic pressure, or project schedule demands. The ASCE Code adds: "Engineers shall be objective and truthful in professional reports, statements, or testimony." These obligations are not aspirational — they are the minimum standard of professional practice. Violation can result in license revocation, civil liability, and criminal prosecution.

Case Study Context: The following failure analysis is based on a composite of real railroad infrastructure failures. Identifying details have been changed. The engineering deficiencies, failure mechanisms, and ethical failures described are drawn from actual NTSB and FRA accident reports. Students are expected to engage with this material with the professional seriousness it warrants — these failures resulted in fatalities.

Failure Analysis Methodology — The NTSB/Forensic Engineering Process

Professional forensic engineering follows a structured investigation process:

1. Preserve the scene — document all physical evidence before any cleanup or repair.
2. Gather background data — maintenance records, inspection reports, design drawings, material certifications.

3. Identify all failure modes — using FMEA or fault tree analysis.
4. Determine the proximate cause — the immediate physical cause of failure.
5. Determine contributing factors — design deficiencies, maintenance lapses, inspection failures, management decisions.
6. Determine root cause — the underlying systemic or organizational factor that allowed the failure to occur.
7. Develop findings and recommendations — specific, actionable, and prioritized by risk.

Fault Tree Analysis — Boolean Logic for Failure Probability

A fault tree maps failure logic using AND gates (all inputs must occur simultaneously) and OR gates (any input causes the output). For an AND gate: $P(\text{top}) = P(A) \times P(B)$. For an OR gate: $P(\text{top}) = 1 - (1 - P(A))(1 - P(B))$.

Students construct a fault tree for a bridge scour failure with three contributing causes: (1) design underestimated 100-year flood Q_{100} ($P = 0.15$); (2) foundation depth insufficient for calculated scour ($P = 0.30$); (3) annual inspection missed progressive scour ($P = 0.40$). Compute overall $P(\text{failure})$ using the fault tree logic. Compare to the acceptable failure probability for a railroad bridge (typically $P_f < 10^{-4}$ per year per AASHTO LRFD).

Risk Matrix — Probability x Consequence

Engineers prioritize remediation using a risk matrix: Risk Score = Probability Rating (1–5) x Consequence Rating (1–5). Consequence ratings for railroad infrastructure:

Score	1 — Minimal	2 — Minor	3 — Moderate	4 — Major	5 — Catastrophic
Consequence	No injury; <\$10k damage	Minor injuries; \$10k-\$100k	Serious injuries; \$100k-\$1M	Fatalities; \$1M-\$10M	Multiple fatalities; >\$10M; environmental disaster
Action Required	Monitor annually	Inspect semi-annually	Remediate within 1 year	Remediate within 90 days	Immediate slow order or closure

Case Study — The Peckman River Bridge Failure (Composite)

In the spring of an unusually wet year, a 62-year-old railroad through-truss bridge over the Peckman River experienced progressive scour undermining of the north abutment. A loaded freight train crossing the bridge at authorized speed caused the abutment to rotate, dropping the north span 18 inches. The locomotive and three freight cars derailed. No fatalities occurred; two crew members sustained injuries. Post-failure investigation revealed the following documented facts:

- The bridge was designed in 1961 for Cooper E-60 loading and a 50-year flood of 2,800 cfs. The 100-year flood had been recalculated in 1998 as 4,100 cfs — 46% higher than the design basis.

- A 1998 hydraulic study recommended scour countermeasures (riprap or sheet pile cutoff wall). The railroad's bridge department received the study but deferred action citing budget constraints.
- Annual FRA-required bridge inspections in 2018, 2019, and 2020 noted "minor scour" at the north abutment. The 2021 inspection form for this item was left blank — the inspector later stated they could not access the underwater foundation due to high water.
- The bridge engineer of record (EOR) who received the 2021 inspection report signed the annual bridge safety certification without noting the incomplete scour inspection.
- Six weeks before the failure, a track maintenance crew reported to the dispatcher that the track profile over the north abutment appeared to have settled 0.5 inches since their last visit. This was not escalated to the bridge department.

Case Study Discussion Questions

Teams analyze the case and address all of the following:

8. Construct a fault tree for this failure. Identify at least 4 contributing causes. Calculate $P(\text{failure})$ given the following estimates: $P(\text{hydraulic underdesign}) = 0.20$; $P(\text{deferred countermeasures}) = 1.0$ (certain, documented); $P(\text{inspection failure}) = 0.35$; $P(\text{settlement not escalated}) = 0.60$.
9. Assign a Risk Score to each of the following hazard states, using the 5x5 matrix above: (a) the 1998 unmitigated scour recommendation; (b) the 2021 incomplete scour inspection; (c) the unreported 0.5-inch settlement. Determine the required action for each.
10. Identify every party who bore a professional or legal obligation at each stage of this failure chain. For each party, state: what was their obligation (citing NSPE or ASCE Code provision), what did they do, and what should they have done?
11. The EOR faces potential license revocation proceedings. Under NSPE Code Canon 1 and the engineering standard of care, evaluate whether the EOR's conduct constitutes: (a) negligence; (b) gross negligence; or (c) willful misconduct. State your legal and ethical basis.
12. A track maintenance employee knew about the settlement and did not escalate it. Under NSPE Code Section III.2 (employees shall act in conformance with their employer's ethical obligations), did this employee have an independent obligation to escalate or report? What protections does federal whistleblower law (49 USC 20109) provide?
13. Write the corrective action plan that the railroad's chief engineer should have implemented in 1998 when the hydraulic study was received. Include: specific actions, responsible parties, timeline, and the risk reduction calculation (how much does $P(\text{failure})$ decrease if each action is taken?).

Synthesis Discussion: The deepest lesson of this failure is not technical — the technical problems were identified and documented years before the failure. The failure was organizational and ethical: a series of individually defensible decisions (defer budget, note minor scour, leave a field blank, not escalate a report) that collectively created a catastrophe. This is the definition of a "normal accident" in complex systems (Perrow, 1984). Engineers who understand this pattern are equipped to interrupt it. Engineers who do not are at risk of participating in it.

Assessment — Lab Module 6

Criterion	4 – Exemplary	3 – Proficient	2 – Developing	1 – Beginning
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Fault Tree Analysis	Fault tree with 4+ contributing causes correctly connected with AND/OR gates; P(failure) calculated using correct gate logic; compared to AASHTO acceptable P _f ; interpretation clear	4 causes; gate logic correct for 3 of 4 connections; P(failure) calculated	3 causes; gate logic partially correct; P(failure) calculated	Causes listed without fault tree structure; P(failure) not calculated
Risk Matrix Application	Risk score correctly calculated for all 3 hazard states; required action determined for each; prioritization justified with consequence reasoning	Risk scores correct; required actions stated; prioritization present	2 of 3 risk scores correct; required actions stated	Risk matrix described but not applied to specific hazard states
Obligation Analysis	Every party identified with specific NSPE/ASCE Code provision cited; obligation, action, and required action stated for each; analysis is specific and legally grounded	All parties identified; Code provisions cited; obligations stated; one party's analysis is generic	Major parties identified; Code referenced generally; obligations stated	Parties identified; no Code citation; obligations stated in general terms
EOR Ethical & Legal Analysis	Negligence vs. gross negligence vs. willful misconduct correctly distinguished with legal definitions; EOR conduct correctly classified with specific factual basis; professional standard of care applied	Classification correct with legal basis; standard of care applied; factual basis stated	Classification stated; standard of care referenced; factual basis weak	Classification stated without legal distinction or factual basis
Corrective Action Plan	Plan includes: specific actions with technical basis;	Plan includes all elements; P(failure) reduction for 2 of	Plan includes actions, parties, timeline; no quantified risk	Plan is a list of actions without parties, timeline, or risk

	responsible parties; timeline; quantified P(failure) reduction for each action; written in professional engineering format	the actions	reduction	quantification
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CAPSTONE

Comprehensive Railroad Infrastructure Assessment

Full Engineering Report — Integrating All Six Lab Modules
Suitable for Honors Designation or Senior Elective Credit

Duration	3–4 weeks (concurrent with or following Lab Modules 1–6)
Team Size	3–4 students; one student designated Engineer of Record (EOR) — rotates
Deliverable	Full engineering assessment report in ASCE/AREMA format: minimum 30 pages plus appendices
Scenario	Teams receive a dossier for a fictional but technically realistic railroad subdivision requiring a comprehensive infrastructure assessment
Oral Defense	20-minute presentation to a panel including at least one practicing PE (invited from local ASCE chapter or railroad industry); 10-minute Q&A

Capstone Client Brief — Pocono Summit Subdivision Assessment

Assignment: Your engineering firm has been retained by the Pocono Summit Short Line Railroad to conduct a Comprehensive Infrastructure Assessment of their 12-mile mountain subdivision. The railroad operates between Stroudsburg and Tobyhanna, Pennsylvania. Maximum authorized speed: 25 mph (FRA Class 2). The railroad has not had a comprehensive engineering assessment in 11 years. Recent events — a wet spring with above-normal runoff, two reported track geometry deviations, and a noise complaint from a crew about a bridge — have prompted the board to commission this report. Your firm's assessment must address all six infrastructure domains from your lab modules and must make specific, prioritized, and costed recommendations.

Required Report Sections

Section 1 — Structural Assessment (Module 1 Integration)

For the three bridges on the subdivision (data provided in dossier): construct influence line diagrams for each; calculate load rating RF for current Cooper E loading; identify any bridge that does not meet the minimum RF for authorized operations; specify the required remediation action and estimate the cost. Include load rating calculations as a formal appendix.

Section 2 — Geotechnical Assessment (Module 2 Integration)

Using the track geometry deviation reports and provided soil boring data: calculate track modulus at the two reported deviation locations; evaluate bearing capacity of the subgrade at the most critical location; estimate settlement risk using 1D consolidation theory; classify the ballast condition against AREMA Chapter 1 and specify any required ballast renewal program.

Section 3 — Transportation & Operations Assessment (Module 3 Integration)

Using the railroad's timetable data: calculate current line capacity using the TRB formula; determine the utilization ratio and M/D/1 queue delays; calculate the reliability index beta for the current schedule; identify any locations where capacity is insufficient and propose improvements (additional sidings, schedule adjustments) with quantified capacity gains.

Section 4 — Hydraulics & Drainage Assessment (Module 4 Integration)

For the two culvert crossings documented in the dossier: calculate design discharge for the 50- and 100-year events (IDF curves provided); evaluate each culvert for inlet/outlet control and headwater adequacy; apply HEC-18 scour analysis to the two bridges; specify any required scour countermeasures or culvert replacements with preliminary sizing.

Section 5 — Construction & Remediation Planning (Module 5 Integration)

Develop a CPM schedule for the highest-priority remediation program identified in Sections 1–4. The railroad's operating season constraint: no track outages longer than 48 hours between April and October. Develop a preliminary budget with earned value monitoring baseline. Identify the critical path and calculate schedule and cost risk using PERT.

Section 6 — Risk Assessment & Professional Responsibility Statement (Module 6 Integration)

Construct a risk matrix for all identified deficiencies. Rank by risk score. Identify any deficiency requiring immediate action (risk score ≥ 16). Write the professional responsibility statement signed by the Engineer of Record: state the scope of the assessment, its limitations, the significant findings, and the EOR's professional engineering judgment regarding continued safe operation. This statement carries the weight of a signed PE document.

Capstone Assessment

Criterion	4 – Exemplary	3 – Proficient	2 – Developing	1 – Beginning
Technical Depth & Accuracy	All six sections contain correct calculations with derivations; all analyses reference appropriate AREMA/AASHTO/FRA standards; prototype scaling correct throughout; calculations independently verifiable from appendices	All sections technically correct; standards referenced; minor derivation gaps; scaling correct	All sections present; 1–2 technical errors; standards referenced; scaling mostly correct	One or more sections missing or with significant technical errors

Integration & Synthesis	Section 6 risk matrix correctly integrates findings from all five technical sections; highest-risk items correctly prioritized; Section 5 CPM schedule addresses the correct scope from Sections 1–4	Risk matrix integrates 4 of 5 sections; prioritization correct; CPM addresses most critical items	Risk matrix present; integrates 3 sections; CPM scope partially aligned with findings	Risk matrix not integrated with technical findings; CPM scope not derived from assessment
EOR Statement	Professional responsibility statement: defines scope and limitations, states significant findings, provides PE judgment on continued operations, uses appropriate professional language, acknowledges what was not assessed	All elements present; professional language; one element incomplete	Scope and findings present; PE judgment vague; limitations not stated	Statement present but does not reflect professional engineering judgment or appropriate language
Oral Defense	All panel questions answered with specific reference to calculations and code provisions; team demonstrates mastery of all six technical areas; EOR clearly leads; within 20 minutes	Most questions answered with calculations; team demonstrates competency in 5 of 6 areas; time managed	Questions answered with some specificity; team competent in 4 of 6 areas; time slightly over	Team cannot answer technical questions beyond surface level; relies on report reading
Report Format & Professionalism	Report meets ASCE publication format: executive summary, table of contents, numbered sections, all figures	Report complete; format mostly correct; 2–3 citation or figure caption errors	Report complete; informal format in 1–2 sections; references incomplete	Report lacks table of contents, figure captions, or reference list

	captioned, all tables numbered, all equations numbered, references in ASCE citation format, signed EOR statement on cover			
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Appendix A — Key Equations by Module

Module	Concept	Formula
1	Influence Line (SS beam, midspan)	$\eta_M(a) = a(L-a)/(2L)$
1	Load Rating Factor (AREMA)	$RF = (C - A1*D)/(A2*L)$
1	Midspan Deflection (center load)	$\delta = PL^3/(48EI)$
2	Characteristic Length (Winkler)	$L_c = (4EI/u)^{(1/4)}$
2	Rail Deflection Basin	$y(x) = y_{max} * e^{(- x /L_c)} * \cos(x /L_c)$
2	Consolidation Settlement	$S_c = (Cc/(1+e0))*H*log10(\sigma_f/\sigma_0)$
2	Time to 90% Consolidation	$t_{90} = 0.848*H_{dr}^2/c_v$
2	Bearing Capacity (Terzaghi strip)	$q_{ult} = c*N_c + q*N_q + 0.5*\gamma*B*N_{\gamma}$
3	Block Signal Capacity	$C_{max} = 3600/H_{min}$ (trains/hour)
3	FOSM Reliability Index	$\beta = (\mu_{T_allowed} - \mu_{T_actual})/\sqrt{\sigma_a^2 + \sigma_t^2}$
3	M/D/1 Queue Wait	$W_q = \rho/(2*\mu*(1-\rho))$
4	Manning's Equation	$Q = (1/n)*A*R^{(2/3)}*S^{(1/2)}$
4	HEC-18 Local Scour	$y_s/y_1 = 2.0*K_1*K_2*K_3*K_4*(a/y_1)^{0.65}*Fr_1^{0.43}$
4	Rational Method	$Q = C*i*A$
5	PERT Expected Duration	$\mu_D = (a+4m+b)/6$
5	Crash Cost Slope	$(Crash\ Cost - Normal\ Cost)/(Normal\ Dur - Crash\ Dur)$
5	Cost Performance Index	$CPI = EV/AC$

5	Estimate at Completion	$EAC = BAC/CPI$
6	Fault Tree AND Gate	$P(\text{top}) = P(A)*P(B)$
6	Fault Tree OR Gate	$P(\text{top}) = 1-(1-P(A))*(1-P(B))$
6	Risk Score	$\text{Risk} = \text{Probability Rating} * \text{Consequence Rating (1-5 scale)}$

Appendix B — O Scale Reference Data

Parameter	O Scale (Model)	Prototype (1:1)
Scale Ratio	1:48	—
Track Gauge	1.25 in	4 ft 8.5 in
1 model inch	—	4 prototype feet
1 model foot	—	48 prototype feet
Weight scale factor	$(1/48)^3 = 1/110,592$	—
Area scale factor	$(1/48)^2 = 1/2,304$	—
O36 curve radius	18 in	72 ft prototype
Cooper E-80 max axle (scaled)	328 grams	80 kips
Typical O Scale loco weight	2–5 lbs	220,000–550,000 lbs prototype
FRA Class 4 track geometry limit	See 49 CFR 213.63	1.25 in cross-level max

Appendix C — Code & Standard References

- AREMA Manual for Railway Engineering (current edition) — arema.org — Chapters 1 (roadway), 8 (bridges), 15 (steel structures)
- AASHTO LRFD Bridge Design Specifications (current edition) — particularly Articles 3.6 (live loads), 6.6 (fatigue), 10.6 (spread footings)
- FHWA HEC-18, Evaluating Scour at Bridges (5th ed.) — available free at fhwa.dot.gov
- FHWA HEC-22, Urban Drainage Design Manual (3rd ed.) — culvert design procedures
- FRA Track Safety Standards, 49 CFR Part 213 — ecf.gov — geometry limits by track class
- FRA Signal System Standards, 49 CFR Part 236 — block signal design requirements
- TRB Report TR-182, Railroad Capacity — free download at trb.org
- NSPE Code of Ethics — nspe.org/resources/ethics/code-ethics
- ASCE Code of Ethics — asce.org/career-growth/ethics/code-of-ethics
- SkyCiv Free Structural Analysis — skyciv.com (frame analysis, truss FEA)
- NTSB Railroad Accident Reports — ntsb.gov/investigations — primary source material for Module 6

O Scale Civil & Structural Engineering Lab Supplement

Junior Civil & Structural Engineering Upper-Division Lab Supplement | O Scale Model Railroading

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