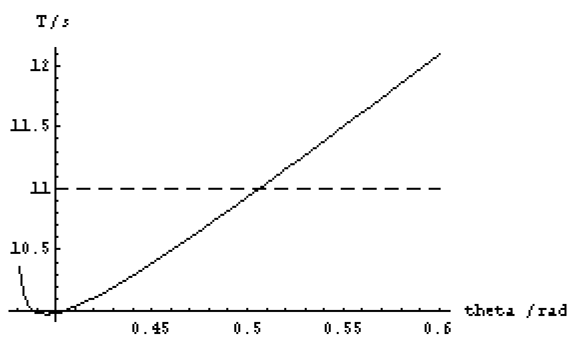
Solution to Question 2: The Rail Gun

Proper Solution (taking induced emf into consideration): (a) Let I be the current supplied by the battery in the absence of back emf. Let i be the induced current by back emf ε_b .		
Since $\varepsilon_b = d\phi / dt = d(BLx)/dt = BLv$, $\therefore i = Blv / R$.	1	
Net current, $I_N = I - i = I - BLv / R$.	0.5	
Forces parallel to rail are: Force on rod due to current is $F_c = BLI_N = BL(I - BLv / R) = BLI - B^2 L^2 v / R$. Net force on rod and young man combined is $F_N = F_c - mg\sin\theta$. (1)	0.5	
Newton's law: $F_N = ma = mdv / dt$. (2)	0.5	
Equating (1) and (2), & substituting for F_c & dividing by *m*, we obtain the acceleration $dv / dt = \alpha - v / \tau$, where $\alpha = BIL / m - g\sin\theta$ and $\tau = mR / B^2 L^2$.	0.5	3

(b)(i) Since initial velocity of rod = 0, and let velocity of rod at time t be $v(t)$, we have $$v(t) = v_\infty\left(1 - e^{-t/\tau}\right), \qquad (3)$$ where $$v_\infty(\theta) = \alpha\tau = \frac{IR}{BL}\left(1 - \frac{mg}{BLI}\sin\theta\right).$$ Let t_s be the total time he spent moving along the rail, and v_s be his velocity when he leaves the rail, i.e. $$v_s = v(t_s) = v_\infty\left(1 - e^{-t_s/\tau}\right). \qquad (4)$$ $$\therefore t_s = -\tau\ln\left(1 - v_s / v_\infty\right) \qquad (5)$$	0.5 0.5 0.5	 1.5

(b) (ii) Let t_f be the time in flight: $t_f = \dfrac{2v_s \sin\theta}{g}$ (6)	0.5	
He must travel a horizontal distance w during t_f. $w = (v_s \cos\theta) t_f$ (7) $t_f = \dfrac{w}{v_s \cos\theta} = \dfrac{2v_s \sin\theta}{g}$ (8) (from (6) & (7))	0.5	
From (8), v_s is fixed by the angle θ and the width of the strait w $v_s = \sqrt{\dfrac{gw}{\sin 2\theta}}$. (9) $\therefore t_s = -\tau \ln\left(1 - \dfrac{1}{v_\infty}\sqrt{\dfrac{gw}{\sin 2\theta}}\right)$, (Substitute (9) in (5))		1.5
And $t_f = \dfrac{2\sin\theta}{g}\sqrt{\dfrac{gw}{\sin 2\theta}} = \sqrt{\dfrac{2w\tan\theta}{g}}$ (Substitute (9) in (8))	0.5	

(c) Therefore, total time is: $T = t_s + t_f = -\tau \ln\left(1 - \frac{1}{v_\infty}\sqrt{\frac{gw}{\sin 2\theta}}\right) + \sqrt{\frac{2w\tan\theta}{g}}$ The values of the parameters are: B=10.0 T, I= 2424 A, L=2.00 m, R=1.0 Ω, g=10 m/s^2, m=80 kg, and w=1000 m. Then $\tau = \frac{mR}{B^2L^2} = \frac{(80)(1.0)}{(10.0)^2(2.00)^2} = 0.20$ s. $v_\infty(\theta) = \frac{2424}{(10.0)(2.00)}\left(1 - \frac{(80)(10)}{(10.0)(2.00)(2424)}\sin\theta\right)$ $= 121(1 - 0.0165\sin\theta)$ So, $T = t_s + t_f = -0.20\ln\left(1 - \frac{100}{v_\infty}\frac{1}{\sqrt{\sin 2\theta}}\right) + 14.14\sqrt{\tan\theta}$ By plotting *T* as a function of *θ*, we obtain the following graph:  Note that the lower bound for the range of θ to plot may be determined by the condition $v_s / v_\infty < 1$ (or the argument of ln is positive), and since mg/BLI is small (0.0165), $v_\infty \approx IR/BL$ (= 121 m/s), we have the condition $\sin(2\theta) > 0.68$, i.e. $\theta > 0.37$. So one may start plotting from $\theta = 0.38$. From the graph, for θ within the range (~0.38, 0.505) radian the time *T* is within 11 s.	Labeling: 0.1 each axis Unit: 0.1 each axis Proper Range in θ: 0.3 lower limit (more than 0.37, less than 0.5), 0.2 upper limit (more than 0.5 and less than 0.6) Proper shape of curve: 0.2 Accurate intersection at $\theta = 0.5$: 0.4	1.5

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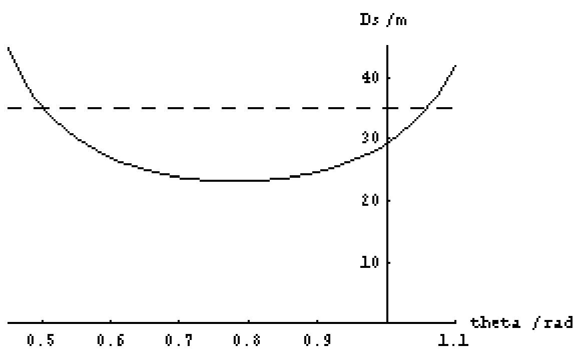
(d)
However, there is another constraint, i.e. the length of rail D. Let D_s be the distance travelled during the time interval t_s

$$D_s = \int_0^{t_s} v(t)dt = v_\infty \int_0^{t_s} \left(1 - e^{-t/\tau}\right)dt = v_\infty \left(t + \tau e^{-\beta t}\right)\Big|_0^{t_s} = v_\infty \left[t_s - \tau\left(1 - e^{-\beta t}\right)\right] = v_\infty t_s - v(t_s)\tau$$

i.e.

$$D_s = -\tau\left[v_\infty(\theta)\ln\left(1 - \frac{1}{v_\infty(\theta)}\sqrt{\frac{gw}{\sin 2\theta}}\right) + \sqrt{\frac{gw}{\sin 2\theta}}\right]$$

The graph below shows D_s as a function of θ.



It is necessary that $D_s \le D$, which means θ must range between .5 and1.06 radians.

In order to satisfy both conditions, θ must range between 0.5 & 0.505 radians.

(Remarks: Using the formula for t_f , t_s & D, we get

At $\theta = 0.507$, t_f =10.540, t_s = 0.466, giving T = 11.01 s, & D = 34.3 m
At $\theta = 0.506$, t_f =10.527, t_s = 0.467, giving T = 10.99 s, & D = 34.4 m
At $\theta = 0.502$, t_f =10.478, t_s = 0.472, giving T = 10.95 s, & D =34.96 m
At $\theta = 0.50$, t_f =10.453, t_s = 0.474, giving T = 10.93 s, & D =35.2 m,
So the more precise angle range is between 0.502 to 0.507, but students are not expected to give such answers.
To 2 sig fig T = 11 s. Range is 0.50 to 0.51 (in degree: 28.6^0 to 29.2^0 or 29^0)

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0.5

Labeling:
0.1 each axis

Unit:
0.1 each axis

Proper Range in θ:
0.3 lower limit (more than 0.4, less than 0.49),
0.2 upper limit (more than 0.51 and less than 1.1)

Proper shape of curve: 0.2

Accurate intersection at $\theta = 0.5$: 0.4

0.5

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2.5

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