Physics Lecture 6 - Testing Hodges' Wheels

Summary/Conclusion

The Friction Test Rig (FTR) and the Virtual Race (VR) model have been applied in the Jobe Consulting labs to examine the performance of the 1999 Standard kit wheel and 5 modifications of this wheel done by Hodges Hobby Shop (WinDerby.com). Of the 6 wheel types, 3 have smooth tread surfaces and 3 have ridged tread surfaces. All 6 have different moment of inertia values in the range of 2 to 5 g cm^2. The 3 smooth tread wheel types behaved as expected but the 3 ridged wheels showed a *much* lower than expected coefficient of friction. The surprising conclusion is that rolling friction must be a much greater contributor to overall wheel friction than previously thought. For smooth wheels rolling friction can actually be as large as friction at the journal bearing (wheel/axle) surface.

Wheel Moment of Inertia

In anticipation of this test, Lecture 5 has already just been published to show how wheel moment of inertia *I* may be calculated. It shows details of calculating *I* for the STD99 wheel. **Figure 1** (next page - would not fit on this page), shows the plots used in the *I* calculations for all 6 wheels by the same procedure as shown in Lecture 5. At the low speeds on the FTR, the only significant decelerating forces are moment of inertia effects and friction, so a precise knowledge of the former allows friction effects alone to be studied.

Experimental Procedure and Results

The FTR rig is shown in Lecture 3. The SBF car used in these tests was also the car shown in Lecture 3. The wheel bore and axle surfaces are prepared using a standard polishing /lubrication procedure described under Speed Package. Then the wheel/axles are installed on the SBF car which is run about 12 times on the FTR. The same 4 nickel plated Hodges' axles are used in all runs. The average of the times is the data plotted by the 6 black squares in **Figure 2** and the standard deviation of the times (on the order of 0.008 s) is shown by the error bars on the measured average times.

Next 6 virtual SBF cars are specified to match the actual SBF car as the 6 different sets of wheels are installed. The overall mass changes slightly and the wheel moment of inertia changes significantly (click here for an example of car parameters input into VR). Then the 6 SBF cars are run in the VR model and at a μ (coefficient of friction) value of 0.068 we have a line as shown by the 6 model times as open square data points.

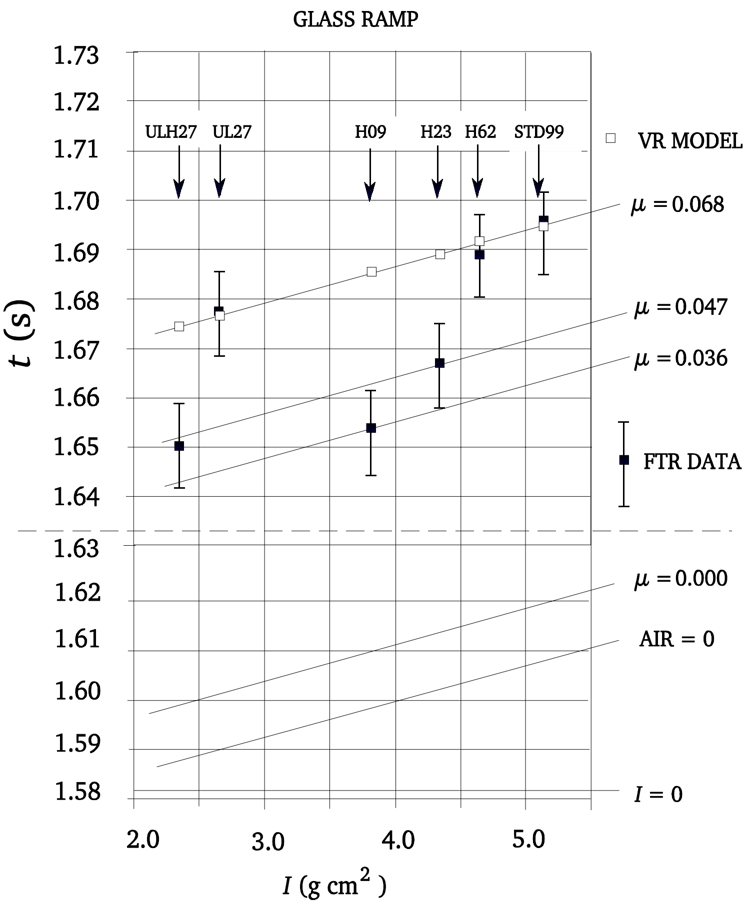

Figure 2. *Showing results of different wheel sets run on the FTR with model data from the Virtual Race program.*

At first, the 3 smooth wheels STD99, H62, and UL27 were run and the VR model predicted the expected increase in speed as the wheel moment of inertia *I* went from 5.123 to 2.654 g cm^2. Next the 3 ridged tread wheels H23, H09, and ULH27 were run with full expectations that they would also show speed increases fully explained by their reduction in *I* as predicted by the open square data points. But, as is apparent form **Figure 2**, the ridged wheels were *much* faster than expected. The FTR was checked, all 6 sets of wheels had their bores resurfaced and relubed, and all axle surfaces were repolished and lubed. The wheels were run an additional 3 times for a total of 4 times with essentially the same results as found in **Figure 2**. Also in **Figure 2**, for information only, there is shown the line for times that occur when friction is set to zero in the VR model and a line for air drag also set to zero. Finally, when *I* is set to zero, you get the line at the bottom at 1.5809 s which is the time for a "perfect" car on the FTR.

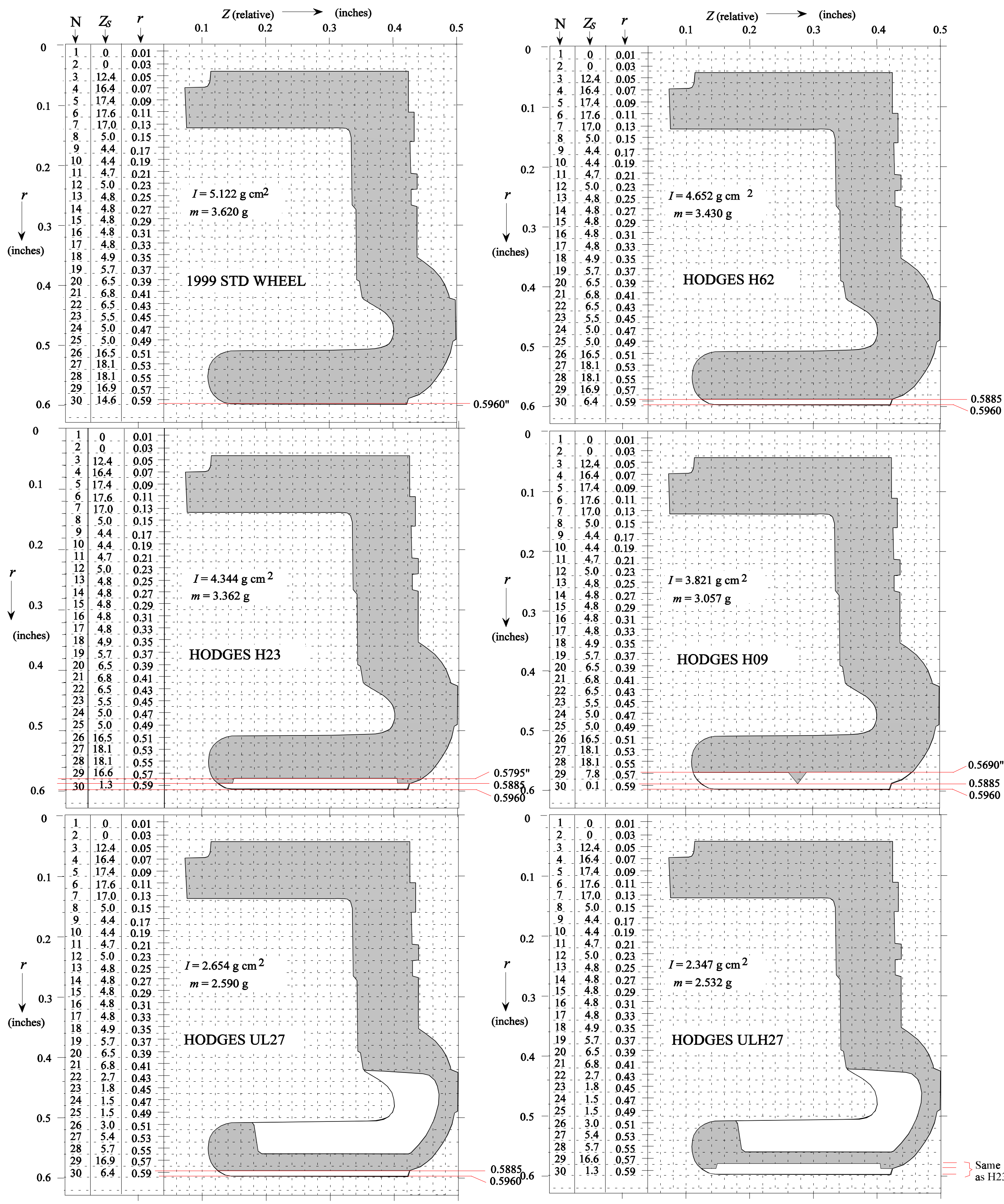

Figure 1. *Cross sections of the 1999 Standard kit wheel and 5 Hodges modifications. The "H" ridged wheels are H23 and ULH 27, which have a ridge on opposite sides of an otherwise smooth tread. The H09 wheel has a single ridge in the center of the tread. Evidently there is not significant distortion of this rather sharp ridge where it makes contact with the track surface. The calculation of wheel I values is the subject of Lecture 4. There it gives a link to an Excel spreadsheet that will compute I and also compute m, the wheel mass as a check (by actual weighing) on I.*

Figure 3 shows the same experiments as **Figure 2** but done with aluminum strips on top of the glass surface. The results are similar to those using the glass-surfaced track except the coefficients of friction are about 0.04 higher. These data should be directly applicable for understanding friction effects on the increasingly popular aluminum tracks.

Table 1 collects the data of **Figures 1** and **2** and breaks it up into sliding and rolling friction based on a hypothesis. This supposition is that, in view of the fact that all bores are exactly the same, the ridge wheel H09 has all its displayed friction resident as the axle/bore sliding type and has minimal, we suppose zero, rolling friction. The hypothesis sounds reasonable because we observe that as the rolling surface apparent contact area increases in H23 and ULH27 so does the observed friction. We also note that the independence of apparent contact area that accompanies tangential sliding friction does not hold for the perpendicular "make and break" type intermolecular forces that are the likely mechanism for rolling friction. Thus, in **Table 1**, we assign the total observed coefficient of friction μ as the sliding type evaluated at the bore surface and call the bore sliding friction μ_{SB}. And for the rolling friction part of the total observed μ of H09 our premise says we will have $\mu_{RB} = 0$. So letting H09 determine what we now think is only axle/bore friction ($\mu_{SB} = 0.036$) we have that what is left over on other wheels must be rolling friction μ_{RB}. It is surprisingly large, at least for this worker, who assumed (as did many others) that the track/wheel surfaces were hard enough and smooth enough to prevent substantial rolling resistance compared to axle/bore friction. So what we see in **Table 1** is that for smooth treaded wheels (the 3 at the bottom of each group of 6) on a glass track the rolling friction is about the same as the axle/bore sliding friction. Moreover, on an aluminum track the rolling appears about twice as large as the bore friction. These μ values are evaluated at the bore surface (radius R_B) because the VR model assumes that is where all the friction is occurring. The actual drag that decelerates a car occurs at the point where the wheel touches the track, so here the friction coefficients must be reduced by the ratio of the bore radius to the wheel radius (a factor of 0.078). Now we see rolling values μ_{RT} that range from zero to 0.0053. This reference http://en.wikipedia.org/wiki/Rolling_friction shows μ_{RT} values from 0.001 for train wheel steel on rail steel to 0.030 for an automobile tire on asphalt pavement. The last 3 columns of **Table 1** show the net positive gravitational acceleration component of *g* along the track and the magnitude of the resistance accelerations. It should be noted that in the finger spin timing method or other methods that measure the decay of free wheel rotation with time, there is no rolling resistance present. However, in these cases air friction resistance effects should sometimes be taken into account.

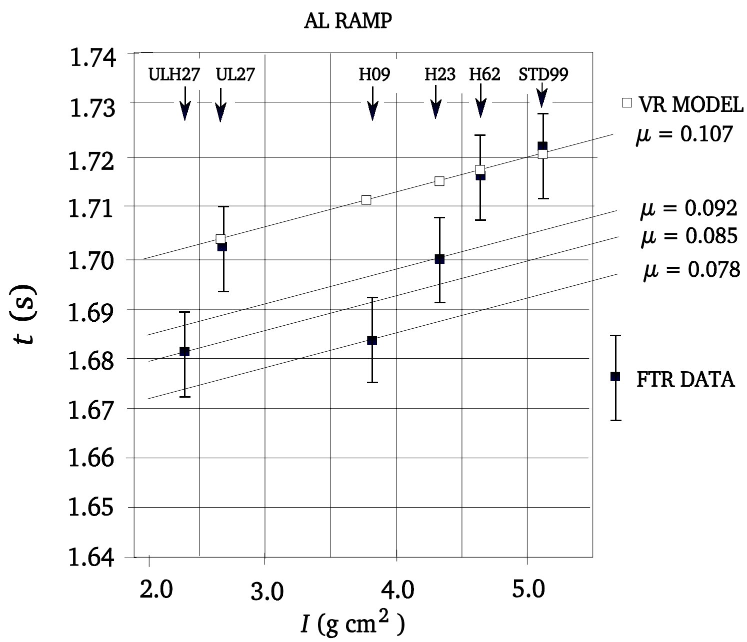

Figure 3. *Showing results for an aluminum surface track.*

Table 1. *Sliding vs. rolling friction for the various wheel types*

WHEEL	TOTAL FRICTION = μ	Evaluated at the bore radius R_B		Evaluated at the wheel radius R_W		GRAVITY ACCEL *g*	DRAG DECEL SLIDE	DRAG DECEL ROLL
		SLIDE = μ_{SB}	ROLL = μ_{RB}	SLIDE = μ_{ST}	ROLL = μ_{RT}			
GLASS TRACK								
HO9	0.036	0.036	0	0.0027	0.0000	75.711	2.629	0.000
H23	0.047	0.036	0.011	0.0027	0.0008	75.711	2.629	0.803
ULH27	0.043	0.036	0.007	0.0027	0.0005	75.711	2.629	0.511
STD99	0.068	0.036	0.032	0.0027	0.0024	75.711	2.629	2.337
H62	0.068	0.036	0.032	0.0027	0.0024	75.711	2.629	2.337
UL27	0.068	0.036	0.032	0.0027	0.0024	75.711	2.629	2.337
ALUMINUM TRACK								
HO9	0.078	0.036	0.042	0.0027	0.0031	75.711	2.629	3.068
H23	0.092	0.036	0.056	0.0027	0.0042	75.711	2.629	4.090
ULH27	0.085	0.036	0.049	0.0027	0.0037	75.711	2.629	3.579
STD99	0.107	0.036	0.071	0.0027	0.0053	75.711	2.629	5.186
H62	0.107	0.036	0.071	0.0027	0.0053	75.711	2.629	5.186
UL27	0.107	0.036	0.071	0.0027	0.0053	75.711	2.629	5.186

Table 2 shows the effects of wheel tread surface treatments on FTR times for both glass and aluminum tracks. The RS polish stands for a compound called rottenstone, which is a decomposed silica-based limestone, and provides a smoother plastic polish than does pumice stone. There is a school of thought that supposes a wheel completely rubbed in graphite, at least the tread surface, will have a beneficial effect by reducing rolling friction. We see from the table that there is a real time reduction of about 0.01 s (corresponding to a μ lower by 0.01) when the graphited wheel is run on an aluminum surface. Finally, the graphite is removed and the wheel surface cleaned using isopropyl alcohol (IPA) which apparently returns the surface to its original condition.

Table 2 - *Smooth tread surface treatment effect on times for glass and aluminum tracks* - *UL27 wheel*

Wheel Surface	FTR time t(s)	Std. Dev.
Glass Track Surface		
RS Polish	1.6763	0.0100
Super-Z	1.6778	0.0085
IPA Clean	1.6752	0.0120
Aluminum Track Surface		
RS Polish	1.6989	0.0880
Super-Z	1.6875	0.0670
IPA Clean	1.6996	0.0750

Discussion

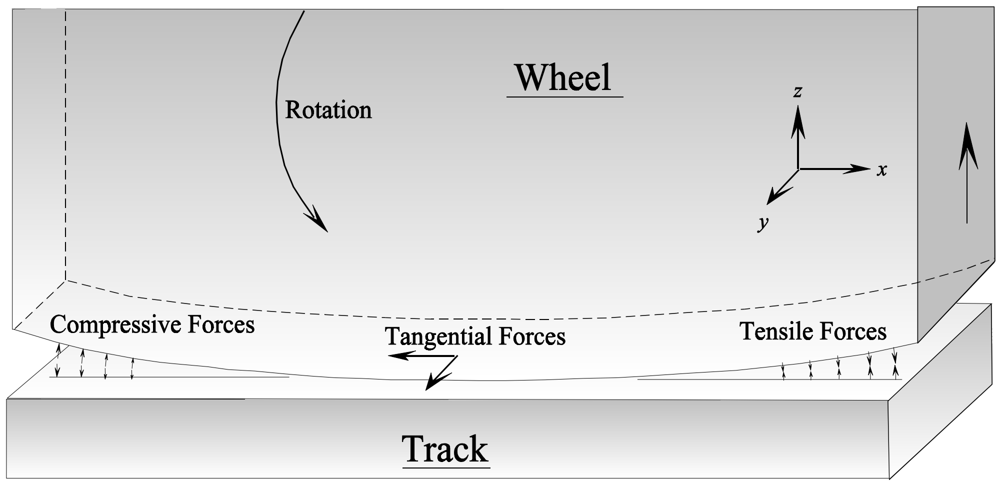

Figure 4. *Perpendicular compressive and tensile forces in rolling friction.*

Figure 4 provides a model to help visualize rolling friction. The magnified sections of wheel and track show that as the wheel rolls to the left (no sliding) it compresses track material, and/or wheel material as well, depending on relative hardness. Later as the wheel contact leaves this area the bonds formed from compression must be broken, leading to tensile forces as the wheel surface leaves the track. These are the perpendicular "make and break" forces in the *z* direction. Some of the energy required to compress material may be stored as potential energy (like compressing a coil spring) that can be recovered as a "push" upwards on the wheel as it rolls forward. However, all of these molecular motions generate heat, which shows up as an inability to recover all the mechanical work expended. Generally, the harder a material the less rolling friction it will have. Regarding glass vs. aluminum, tempered glass is two to three times harder (and smoother) which accounts for less rolling friction on such surfaces.

It is surprising that a graphite coated wheel surface shows some modest benefit on aluminum. Graphite only reduces sliding tangential forces, not perpendicular rolling forces. But it may be that there are electrostatic forces generated in the "make and break" rolling action similar to other well known triboelectric effects. The clean polystyrene wheels will hold static charges because they are good insulators, but a solid coating of graphite, which is a conductor like aluminum, would likely prevent electrostatic effects. Be aware that graphited wheel surfaces compromise wheel stability in the *y* direction (cross-track) allowing the rear end of cars to possibly begin "fish tailing" with center strip bumping and overall loss of speed. Note also that wheel stability in the *y* direction is independent of the surface contact area, i.e., a ridged surface slides cross-track just as easily as a wide smooth wheel surface does (This is described fully in the Physics of the Pinewood Derby book).

The VR race simulator does not specifically require rolling friction to be input separately as a parameter, and assumes that this and other friction types may be captured by simply making the μ value applied at the bore surface larger. These other friction sources could be wheel inside/center strip rubbing or hub/body contact. As demonstrated here, the VR model accurately accounts for 3 of the major effects on race time, namely center of mass position (held constant here), wheel moment of inertia, and air resistance. What is left over is friction, which can now be more effectively modeled based on tread design. It is interesting to recall back in 1990 that the standard kit wheels were rather poorly molded. So occasionally a sharp seam of material would appear in the otherwise smooth tread center reminiscent of the H09 wheel above. Rumor had it that such wheels were fast, and everyone tried to find a kit that contained such wheels since they were legal by definition. Speaking of legality, what if H09 had a knife-edge strip of hard blackened steel only a fraction of a mil high? Or what if the tread were uniformly concave just a few mils deep in the center(the STD99 wheel already approximates this)? There is more work to do in this area.